A software tool for computing Solar Wind Speed through Doppler dimming diagnostics

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& **Metis Team**

January 25th, 2024

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[3] INAF - Astrophysical Observatory of Palermo, Italy, [4] Astronomical Observatory of Capodimonte, Napoli, Italy,
[5] INAF - Astrophysical Observatory of Arcetri, Florence, Italy

9th Metis Workshop - Catania, 24-26, January **2024**

A ... ed

Silvio Gior ... . Burtovoi[5]

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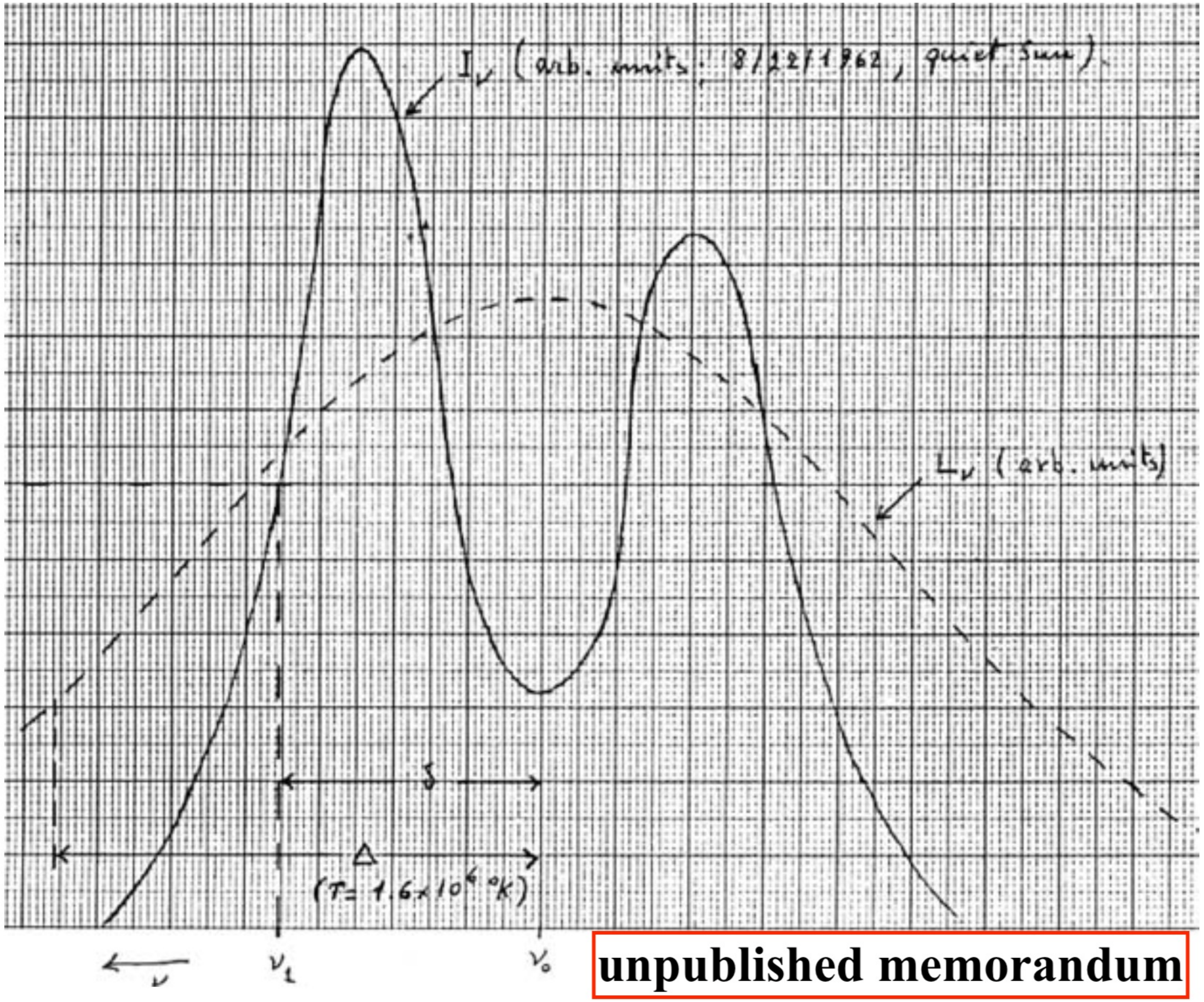
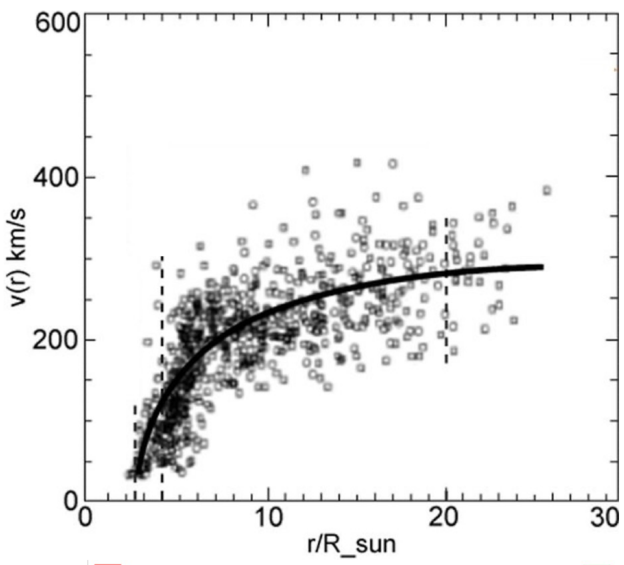


Noci's (1973a) illustration of the overlap between the disk H I Lyα profile and the broader coronal scattering profile, which drives the Doppler dimming effect

“*Some*“ Wind Speed determinations in Solar Corona



Rocket UVC (H I Lyα) & WLC (pB) - Coronal Hole at 2 Rs, u = 217^{+34}_{-64} km/s, *Strachan+ 1993*

LASCO/SOHO Wight light **Streamer** Blobs, *Sheeley+ 1997*

UVCS/SOHO Oxygen ions speed **map,** *Giordano+ 1997*

UVCS/SOHO Proton speed **Coronal Hole,** *Cranmer 2009*

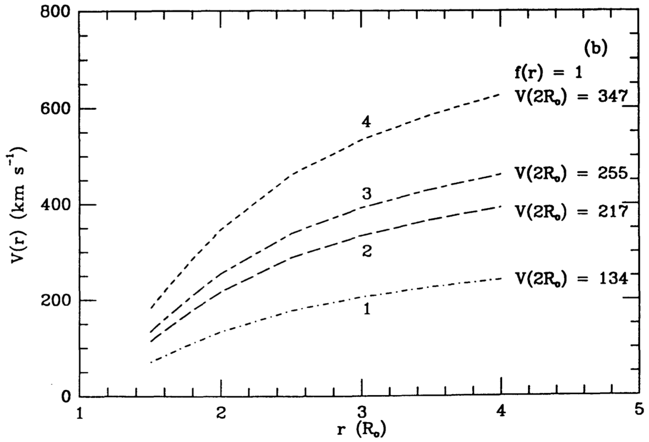
STEREO-A/COR2 Intermittent inhomogeneous Fine Structures, *Deforest+ 2018*

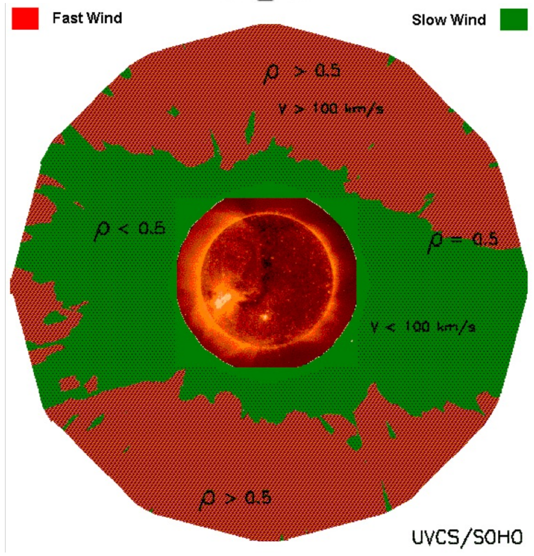
Comets H I Lyα UVCS/SOHO at **6 Rs**, u = 75 ± 25 km/s, *Giordano+ 2015*

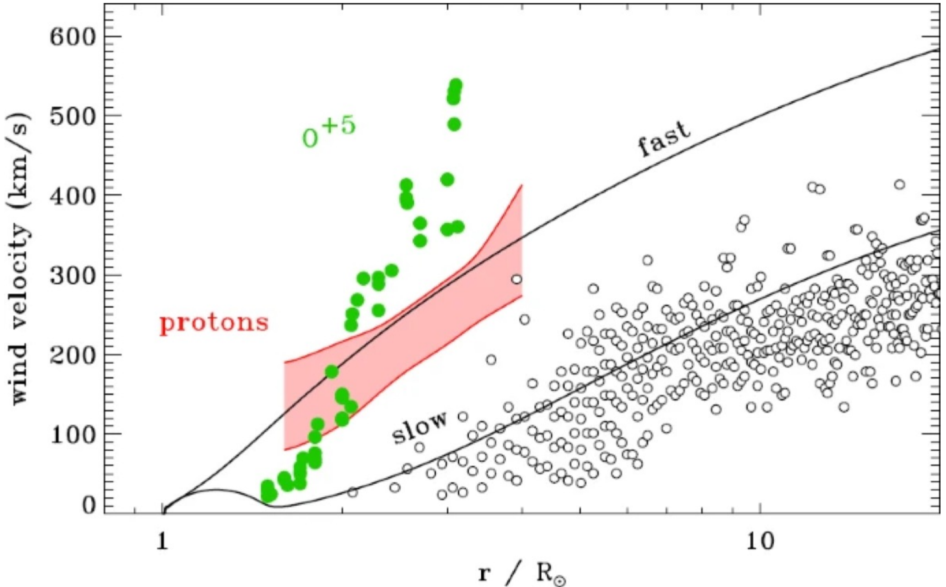
Metis/SO at **14 Rs**, u = 190 ± 50 km/s, *Bemporad+ 2023*

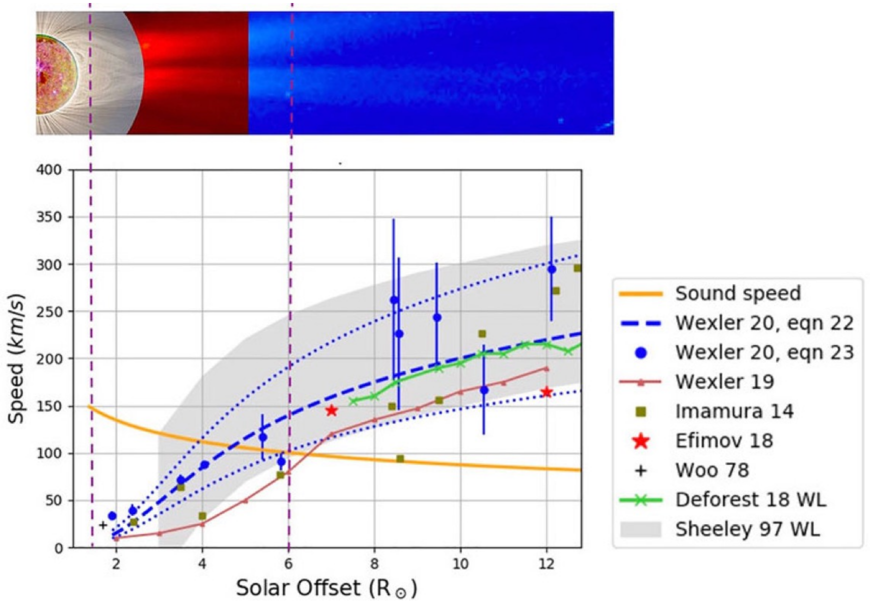
Radio scintillations

PSP In-situ *that is* in the Solar Corona





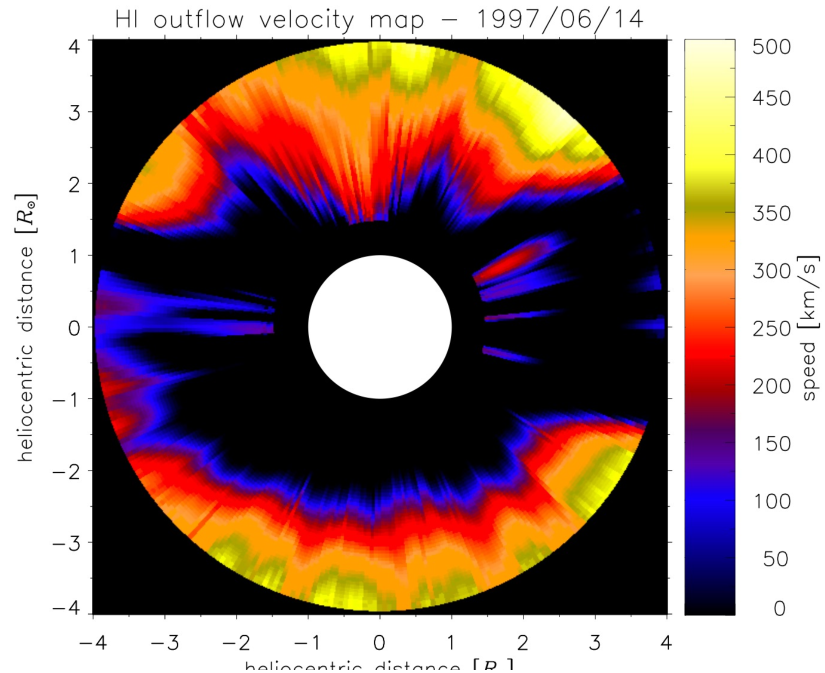


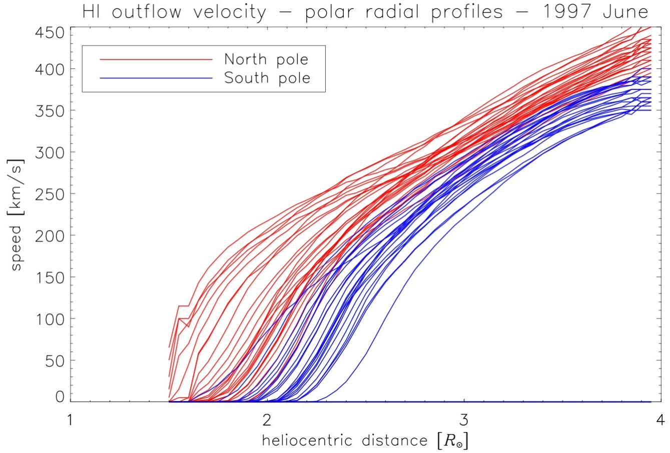


“*Doppler dimming*“ Wind Speed determinations in Solar Corona

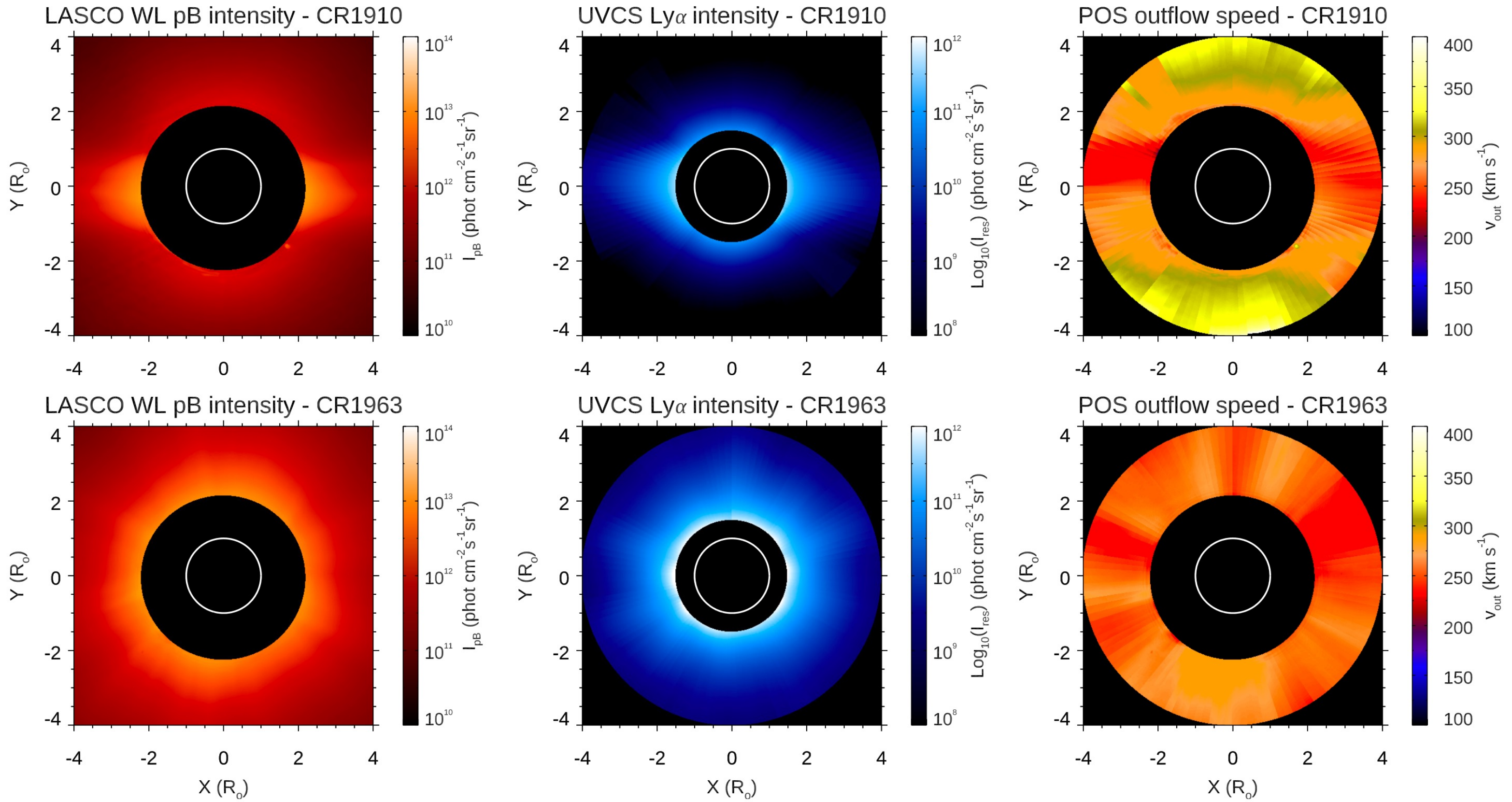
UVCS/SOHO Proton speed **maps**

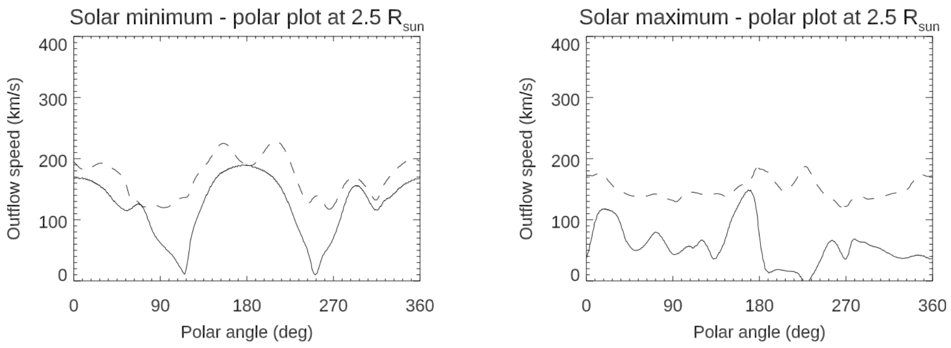
Doppler Dimming Inversion - *Dolei+ 2018*





Doppler Dimming *Quick* Inversion - *Bemporad+ 2021*

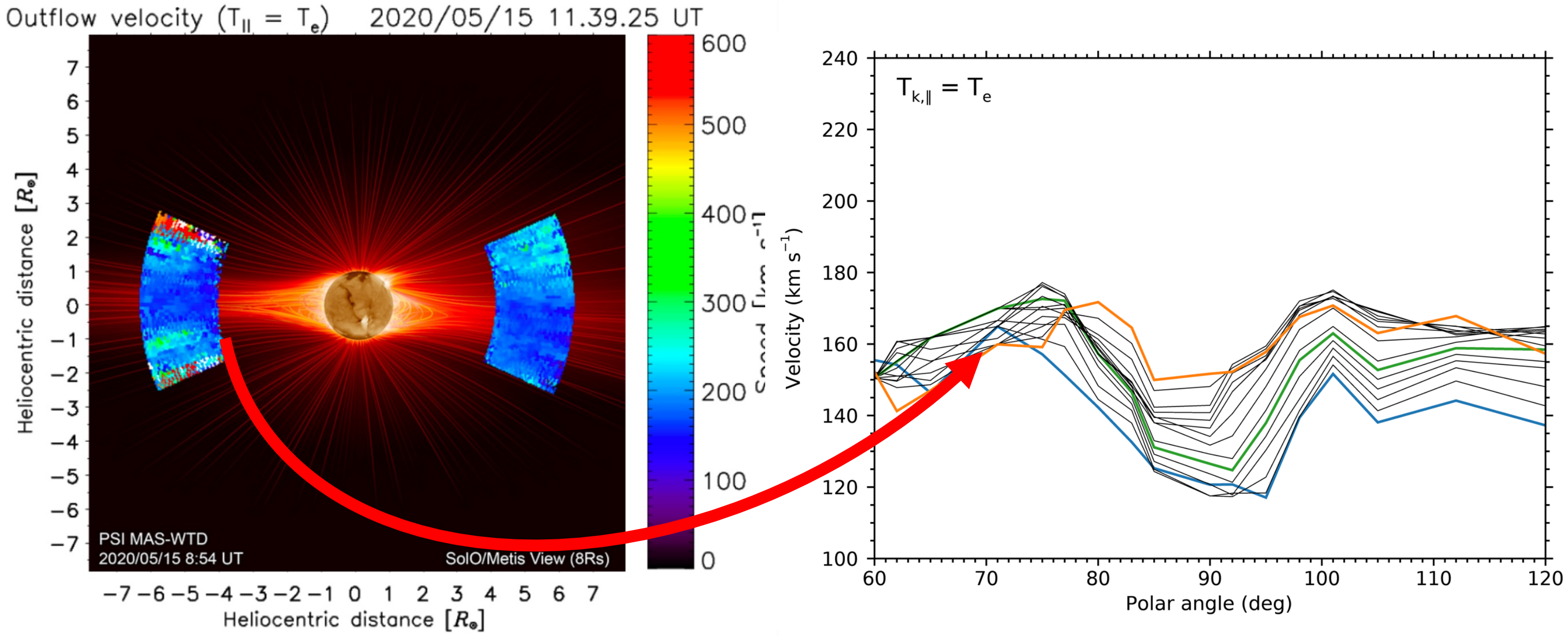


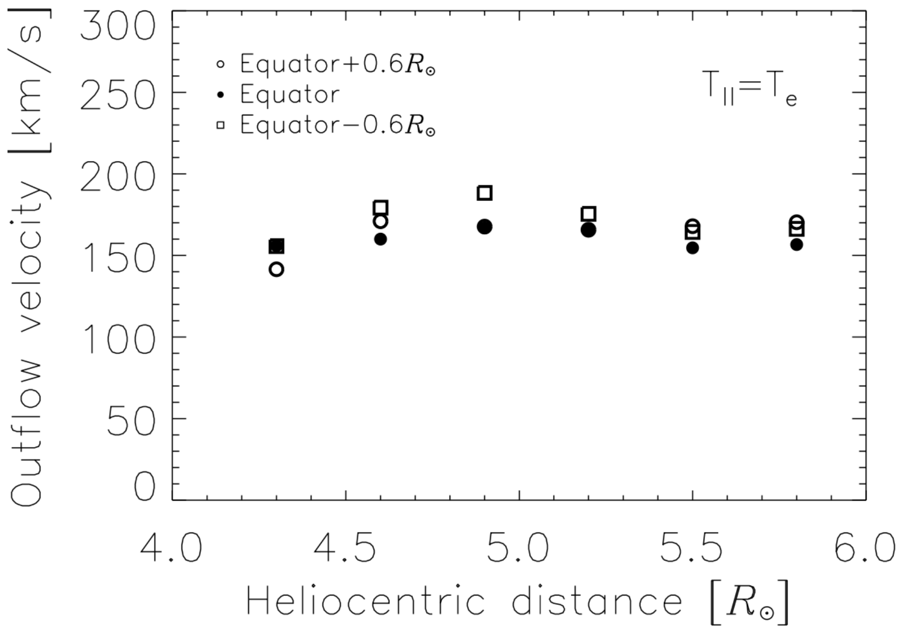


"*Doppler dimming*" Wind Speed determinations in Solar Corona

Metis/SO wind speed map **Equatorial Region** - *Romoli+ 2023*

METIS/SO Proton speed **maps**

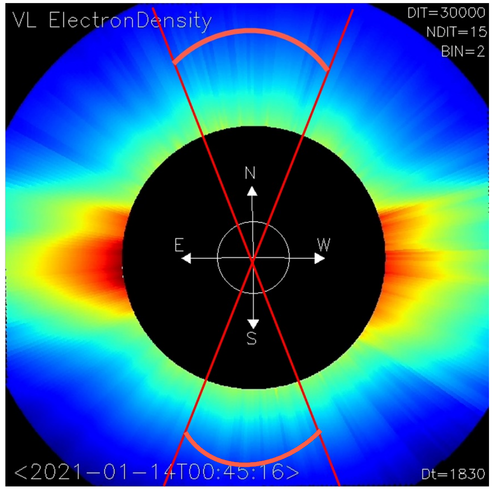




UVCS/SOHO + Metis/SO wind speed in **Polar Coronal Hole** - *Telloni+ 2023*

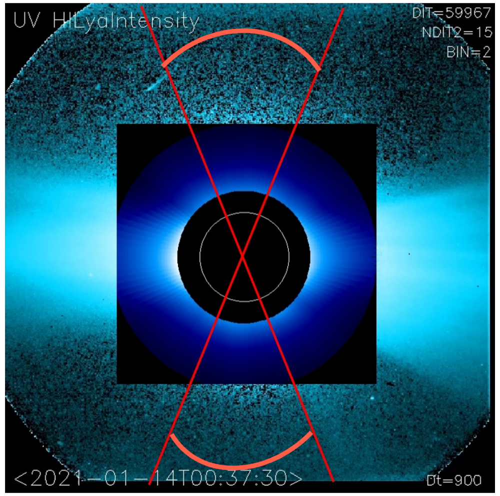
Electron Density

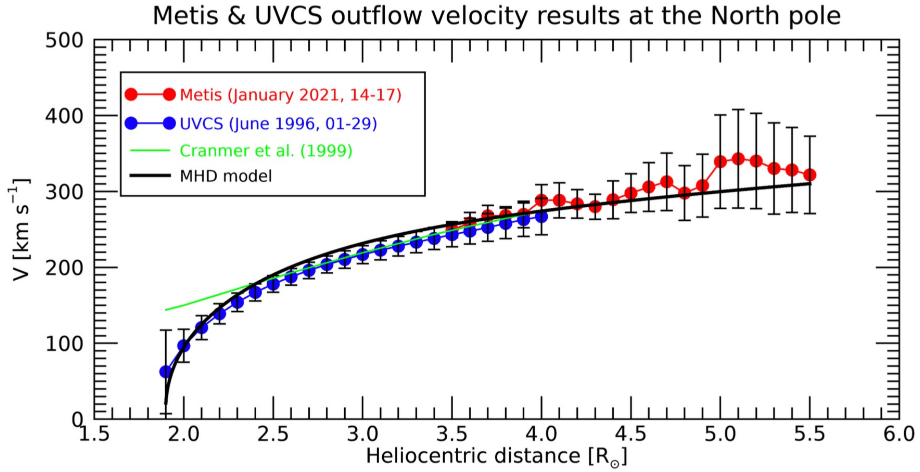
Metis
+
LASCO



H I Lyα

Metis
+
UVCS





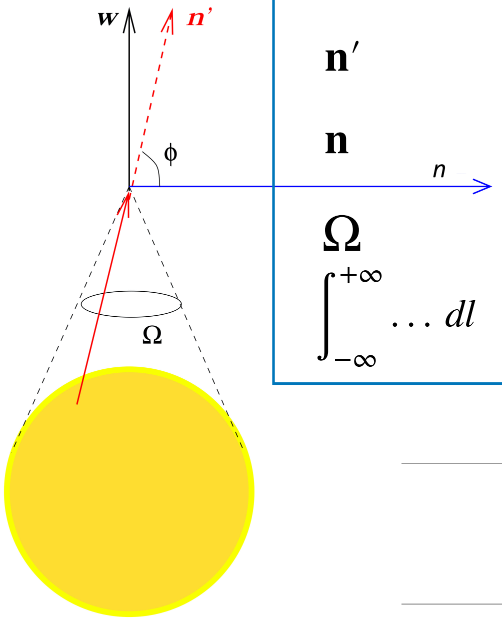
H I Lyα 1215.67A Radiative Component

$$I_{obs} \simeq I_r = \frac{b\, B_{12}\, h\, \lambda_0}{4\pi} \int_{l.o.s} n_{HI}\, dl \int_{\Omega} p(\mathbf{n} \cdot \mathbf{n}')\, d\Omega \int_0^{+\infty} I_{ex}(\lambda - \frac{\lambda_0}{c}\, \mathbf{u} \cdot \mathbf{n}')\, \Phi(\lambda, T_{\mathbf{n}'})\, d\lambda$$

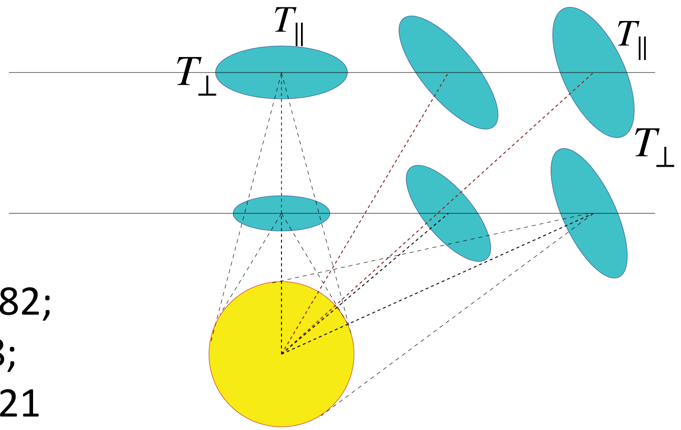
$$n_{HI} = \frac{1}{1 + 2A_{He}}\, n_e\, R_{HI}(T_e)$$ Neutral Hydrogen density

$\Phi(\lambda, T_{\mathbf{n}'})$ Absorption Profile

$$I = \mathcal{F}(I_{ex}(\lambda), A_{He}, n_e, T_e, T_p, K_i, \boldsymbol{u})$$



Geometry	
$\mathbf{n}'$	exciting radiation direction
$\mathbf{n}$	scattering direction
Ω	solid angle
$\int_{-\infty}^{+\infty} \dots\, dl$	l.o.s. Integration



Noci+ 1973; Withbroe+ 1982;
Noci+ 1987; Dodero+ 1998;
Dolei+ 2015; Capuano+ 2021

H I Lyα Intensity is a function of	
$I_{ex}(\lambda)$	Specific Intensity of Chromospheric radiation
A_{He}	Helium Abundance
n_e	Coronal Electron Density
T_e	Coronal Electron Temperature
T_p	Coronal Proton Temperature
$K_i = \frac{T_{\perp}}{T_{\parallel}}$	Anisotropy factor
$\boldsymbol{u}$	**Outflow Speed**

H I Lyα 1215.67A Radiative Component

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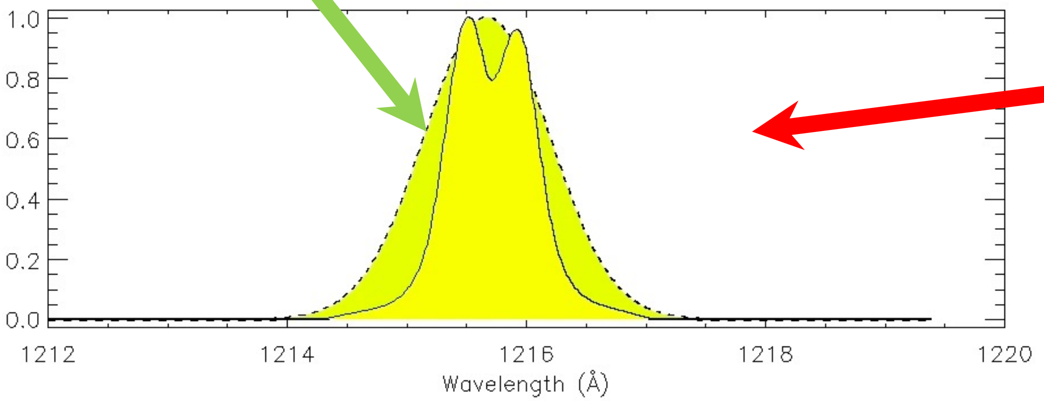

H I Lyα Intensity is a function of

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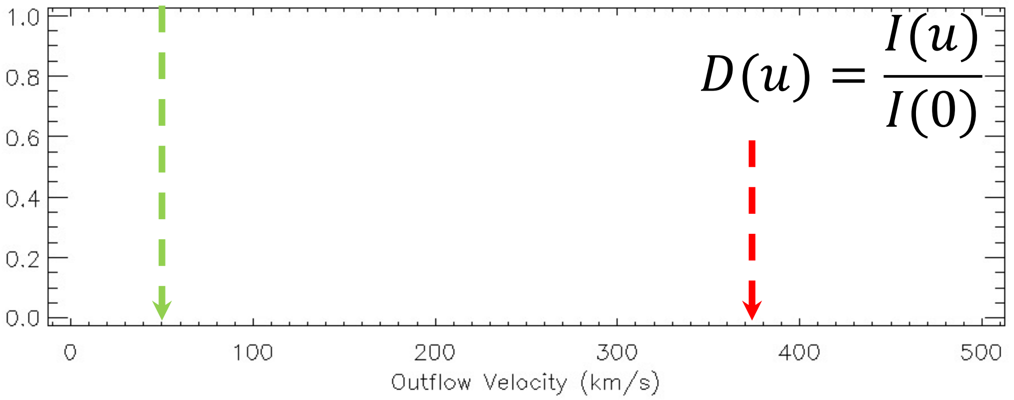
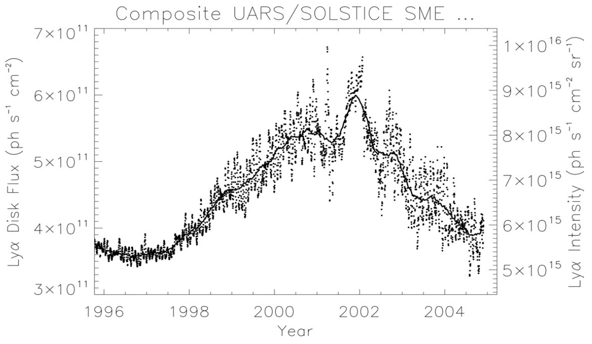
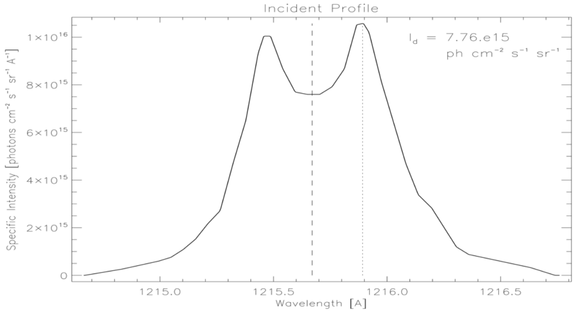


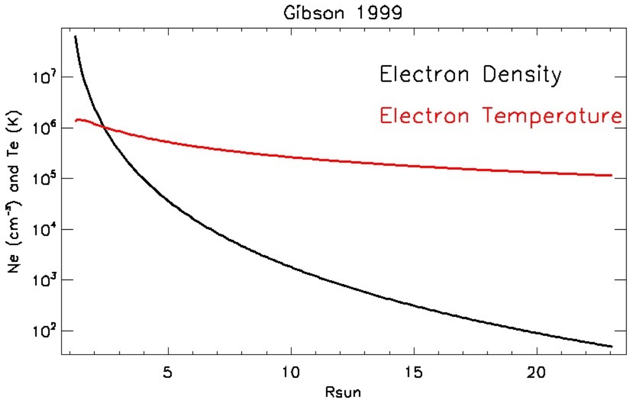
Doppler Dimming Diagnostic: Parameters

$$I = \mathcal{F}(I_{ex}(\lambda), A_{He}, n_e, T_e, T_p, K_i, \boldsymbol{u})$$

I_{obs}	Observed H I Lyα Intensity	Metis UV images	measurement uncertainty
n_e	Electron Density	Metis pB images	measurement uncertainty
$\int I_{ex} d\lambda$	Disk intensity	LASP Interactive Solar Irradiance Datacenter https://lasp.colorado.edu/lisird/	daily variation, not uniform
$I_{ex}(\lambda)$	Disk profile	Analytical (Auchère 2005) or empirical (Lemaire+ 2002)	negligible *
T_e	Electron Temperature	Models, Literature, constant value **	
T_p	Proton Temperature	UVCS Temperature images of H I Lyα line Width **	
K_i	Anisotropy factor	values: 1 (isotropy), 2 (maximum anisotropy) **	
A_{He}	He Abundance	values: 10% (typical), 2.5% (Moses+ 2019) **	





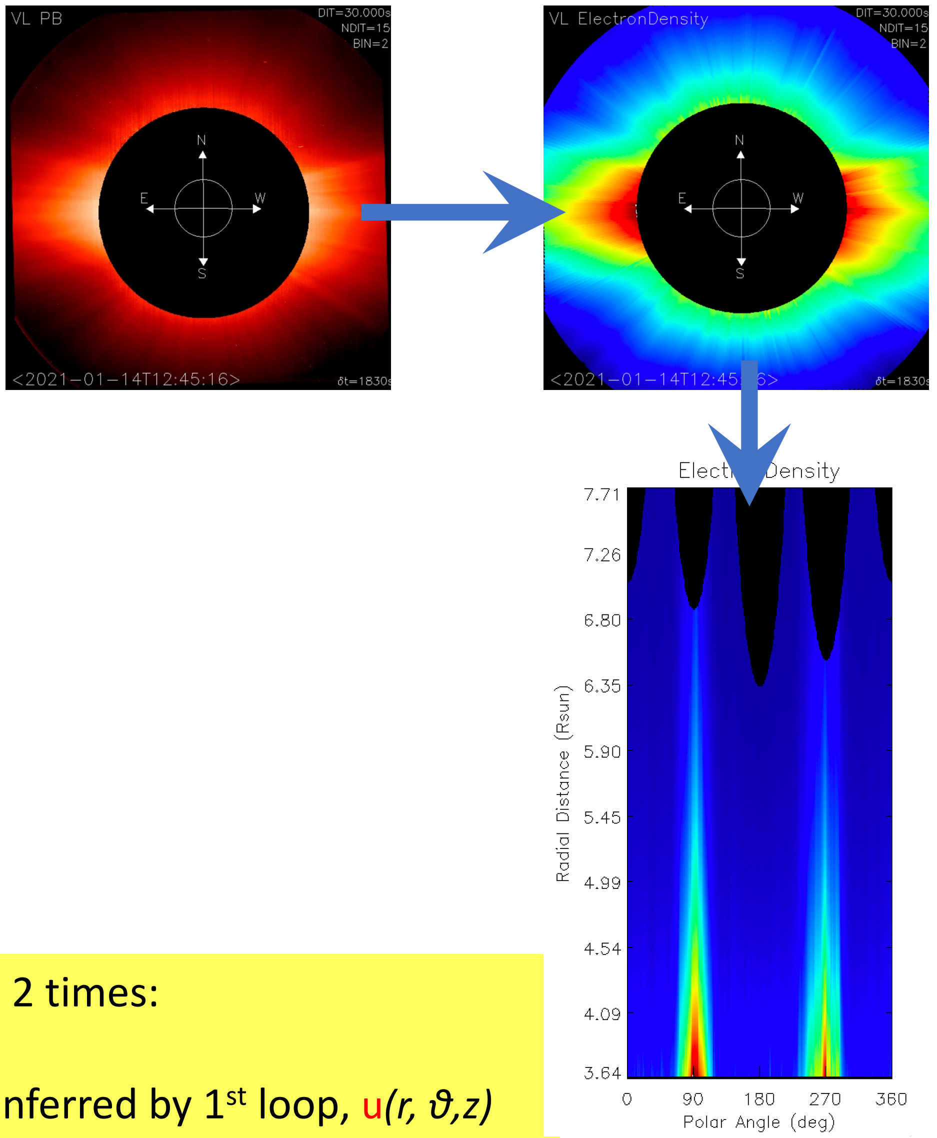


* Dolei+ 2018, ** Dolei+ 2019

Doppler Dimming Tool (DDT)

code flow - iterative method

$$I_{syn} = \mathcal{F}(I_{ex}(\lambda), A_{He}, n_e, T_e, T_p, K_i, \boldsymbol{u})$$



Get *pB(x,y)* observation → compute electron density n_e*(r, ϑ)*

Compute n_e *(r, ϑ, z)*, 3D distribution in cylindrical symmetry

Get model: $I_{ex}(\lambda), A_{He}, T_e, T_p, K_i$

Compute T_e, T_p, K_i A_{He} 3D distribution in cylindrical symmetry

Loop over map elements *(r, ϑ)*

- Set u*(r, ϑ)* = 0 km/s
- Get T_e, T_p, K_i A_{He} along the LOS *(r, ϑ, z)*
- Compute Synthetic H I Lya Emissivity j_{syn} *(r, ϑ, z)*
- Integrate along the LOS → Synthetic H I Lya Intensity I_{syn}*(r, ϑ)*
- Compare I_{syn}*(r, ϑ)* to I_{obs}*(r, ϑ)*
- Adjust u *(r, ϑ)* iteratively

==> Save Wind Speed Map

the Loop is performed 2 times:

1st Contant **u** along the LoS, u*(r, ϑ)*

2nd **u** profile along the LoS as radial profile inferred by 1st loop, u*(r, ϑ,z)*

Code History: *Withbroe & Noci 1987, Noci ~1990, Dodero ~2000, Dolei ~2015, Giordano, Capuano, Zangrilli and more ~2020 to present*

Doppler Dimming Tool (DDT)

code flow - iterative method

Compute n_e *(r, ϑ, z)*, 3D distribution in cylindrical symmetry

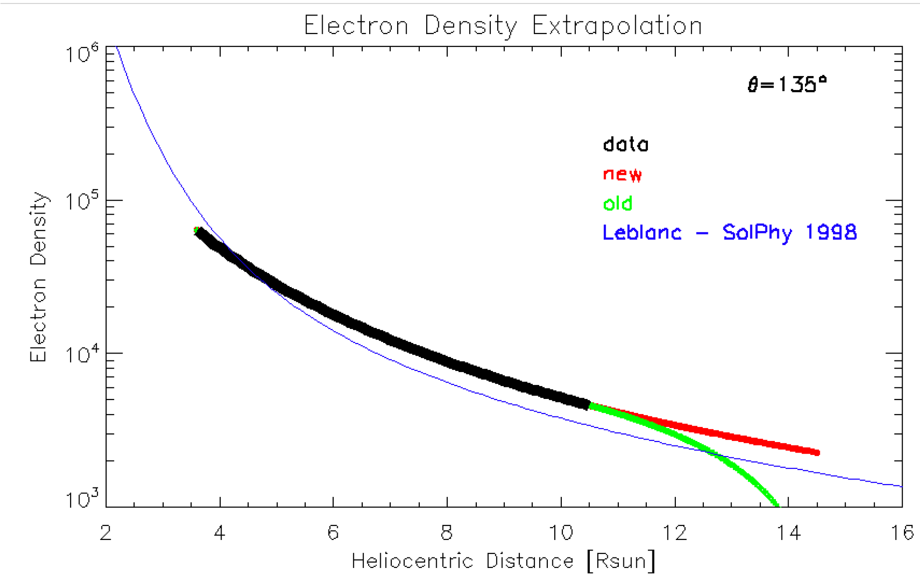
2nd **u** profile along the LoS as radial profile inferred by 1st loop, u*(r, ϑ,z)*

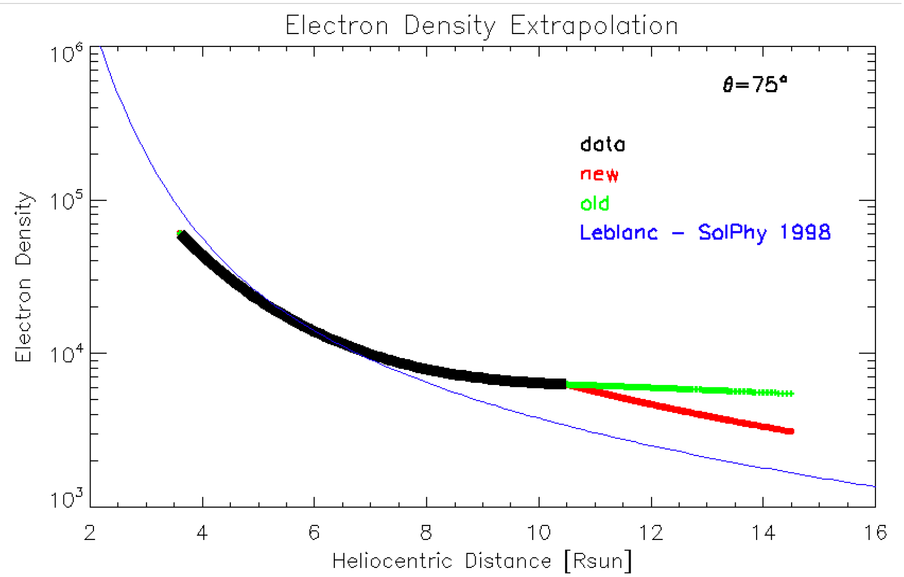
Doppler Dimming Tool (DDT)

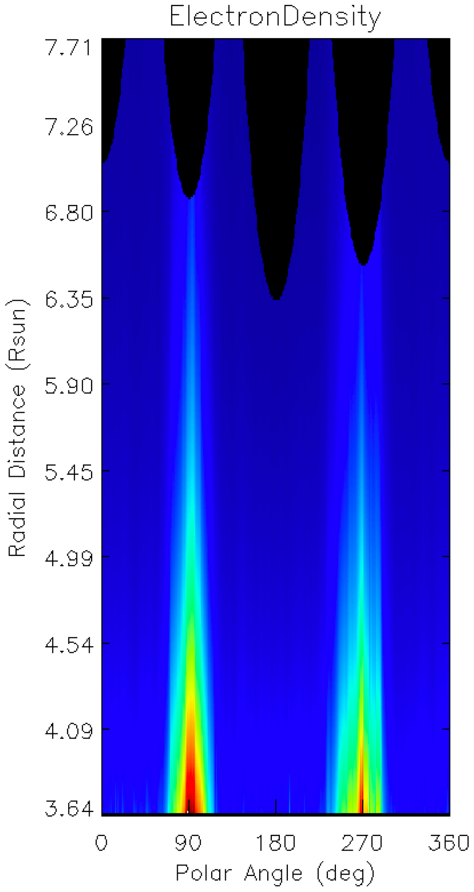
code flow - iterative method

Compute $n_e(r, \vartheta, z)$, 3D distribution in cylindrical symmetry

Extrapolation along the LoS at larger than observed height is necessary







Doppler Dimming Tool (DDT)

code flow - iterative method

2nd Loop: **u** profile along the LoS as radial profile inferred by 1st loop, u*(r, ϑ,z)*

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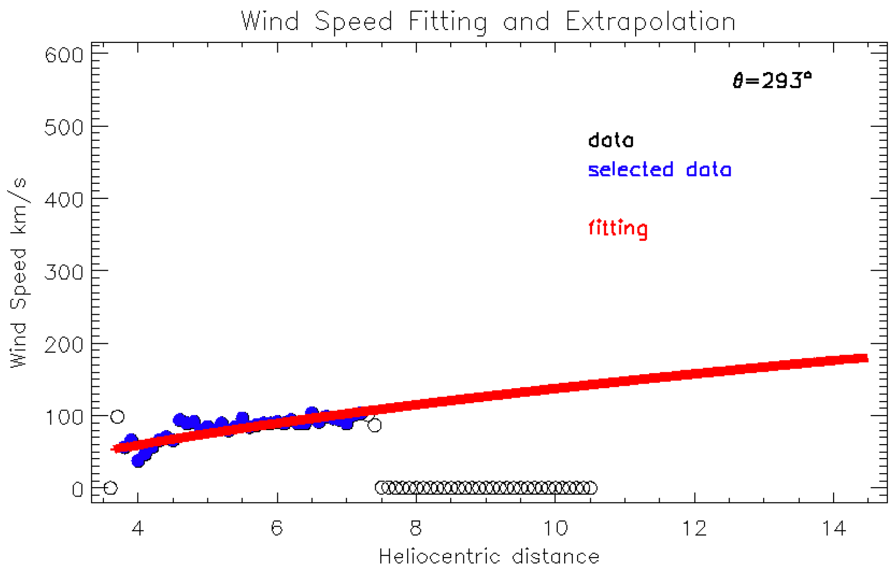
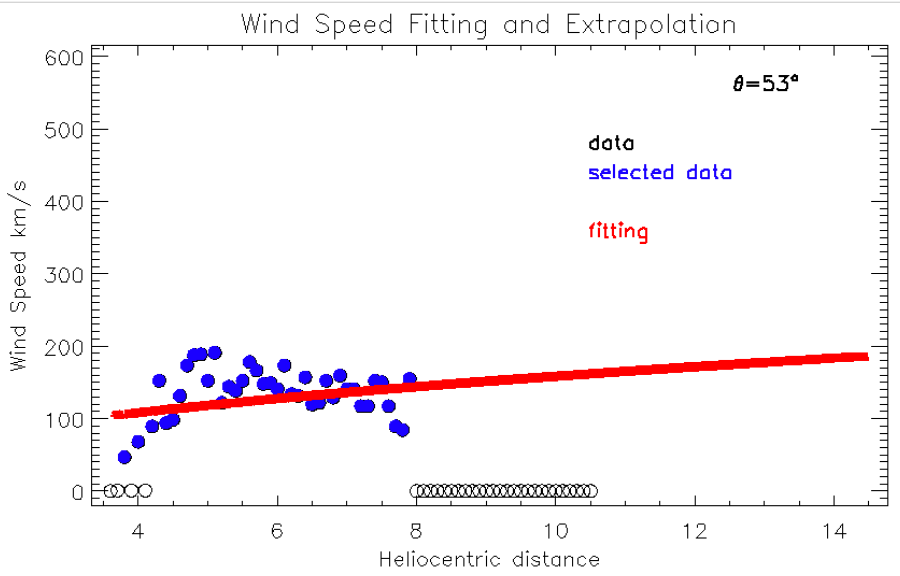
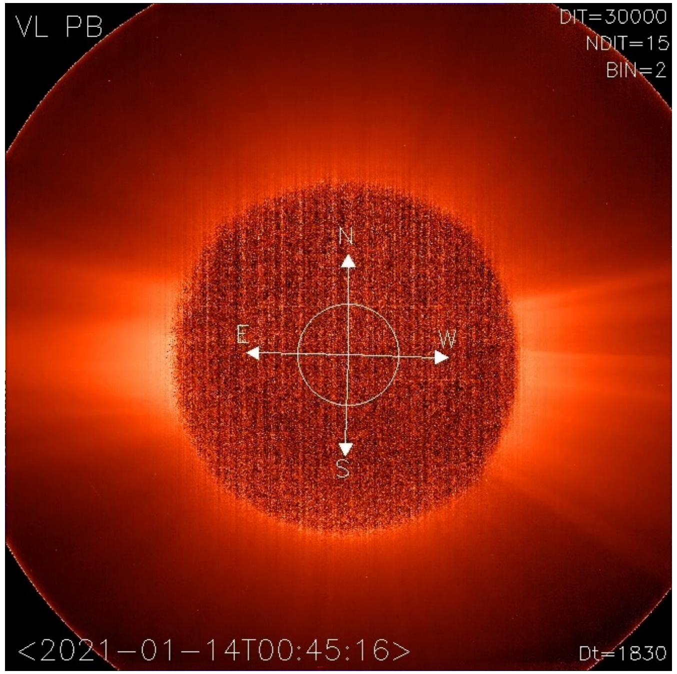




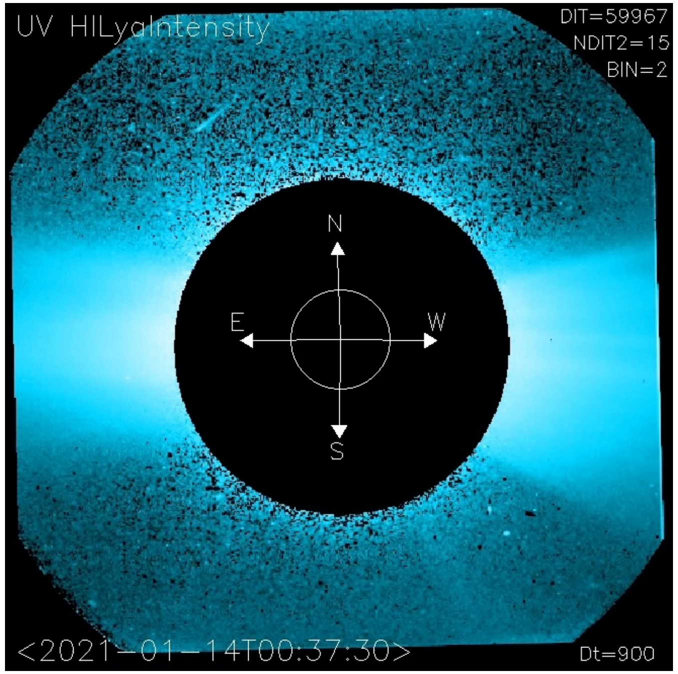
Doppler Dimming Tool (DDT) Results

- Metis/SO observation: January 14-17, 2021

Polarized Brightness



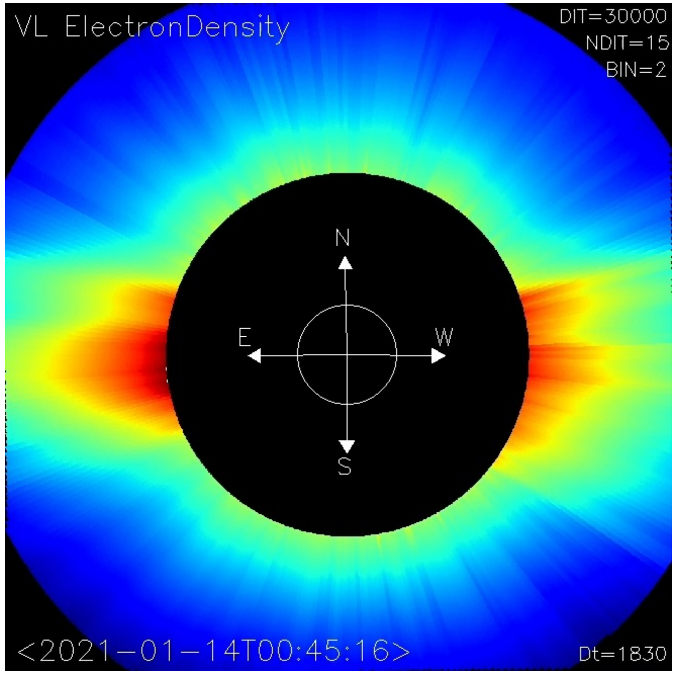
H I Ly-alpha Intensity



Doppler Dimming Tool (DDT) Results

- Metis/SO observation: January 14-17, 2021

Electron Density



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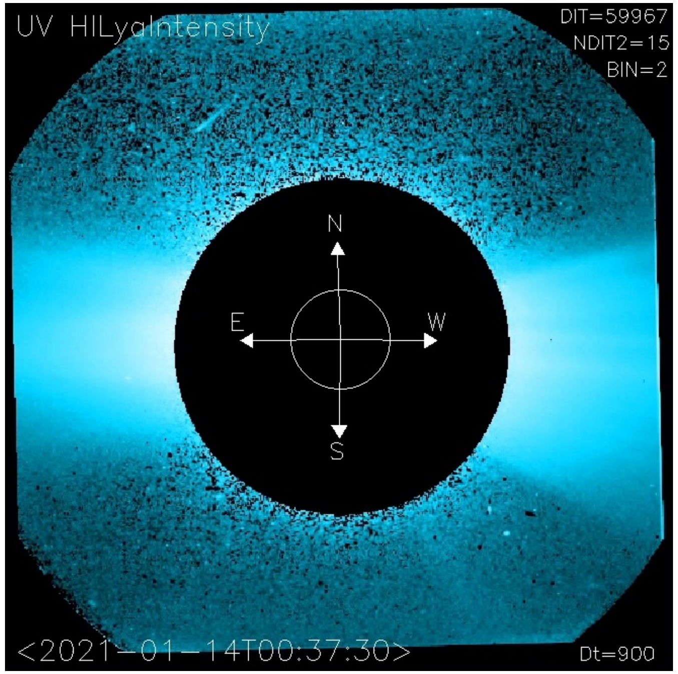
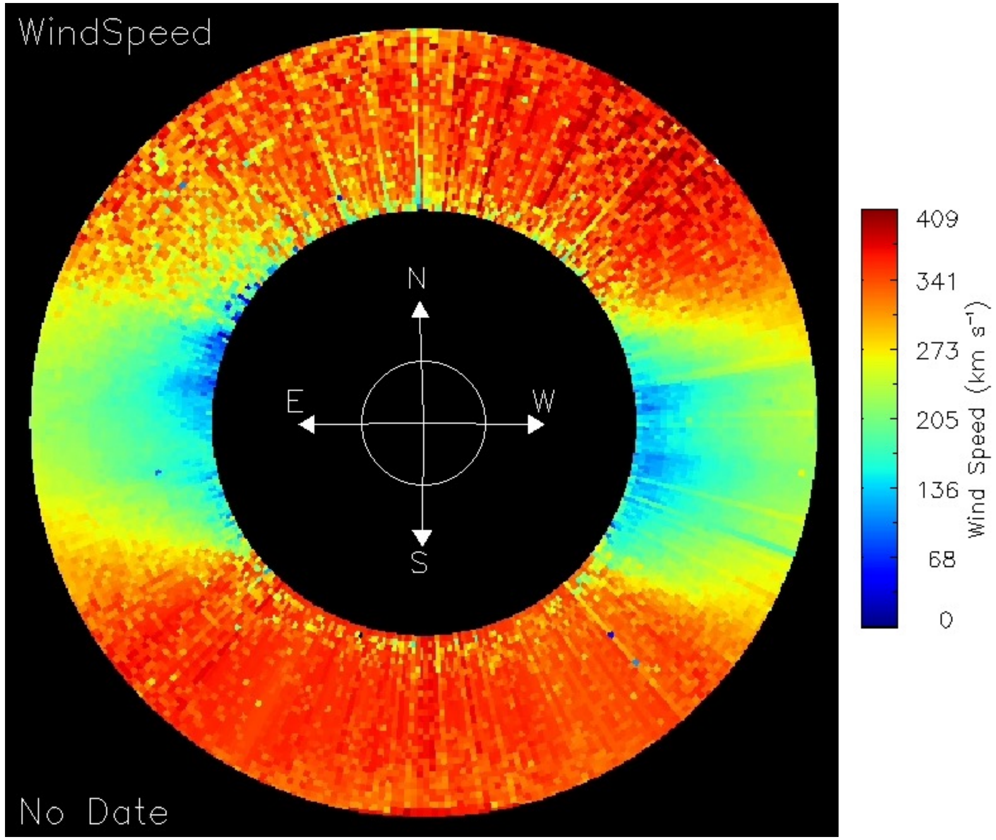


Wind Speed

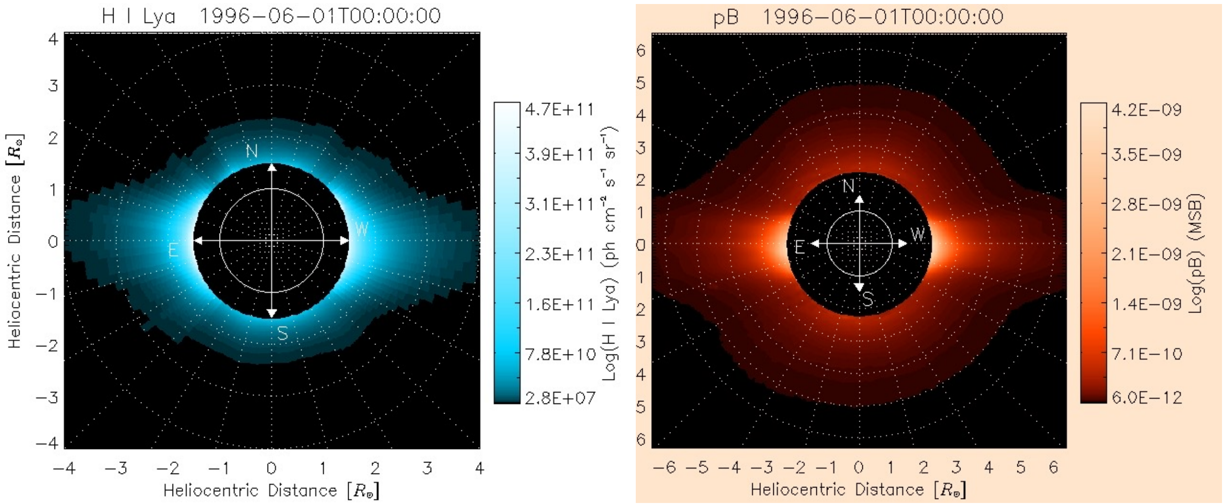


Solar Wind Speed Maps from Metis/Solar Orbiter

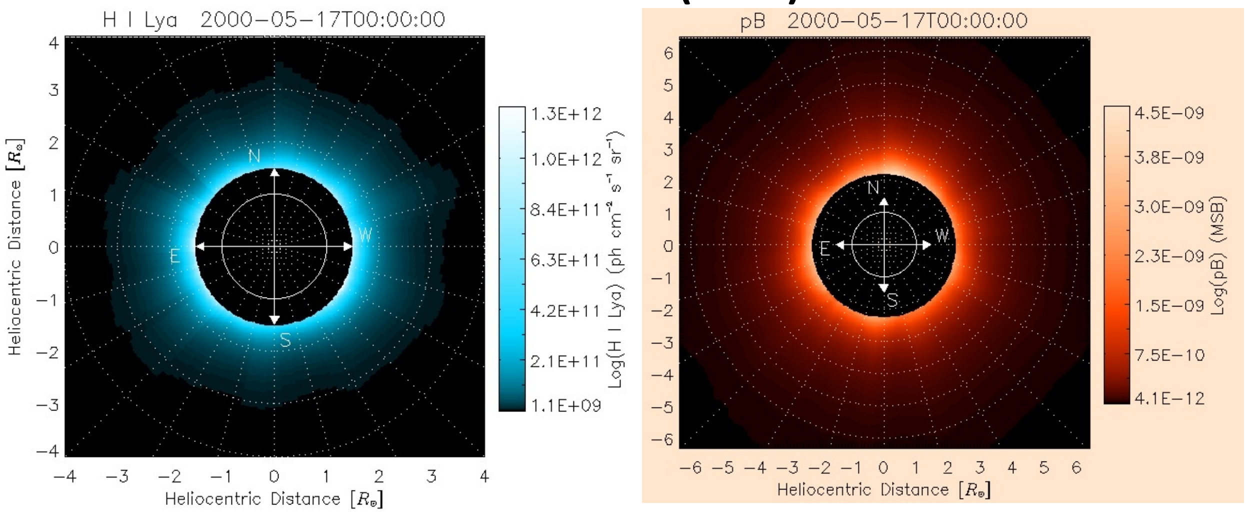
Giordano+ 2024 in preparation

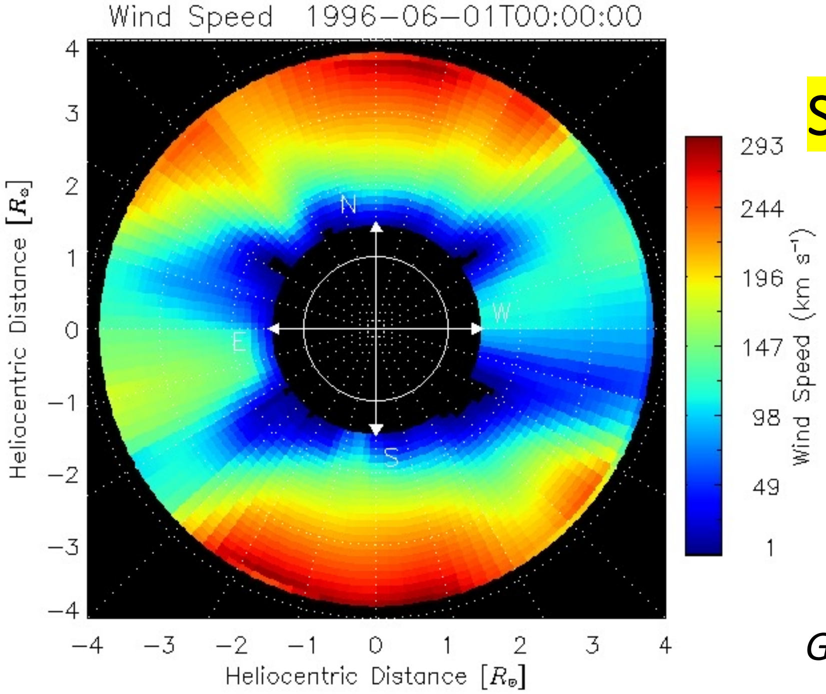
Doppler Dimming Tool (DDT) Results

Solar Minimum (1996)



Solar Maximum (2000)





Solar Wind Speed Maps

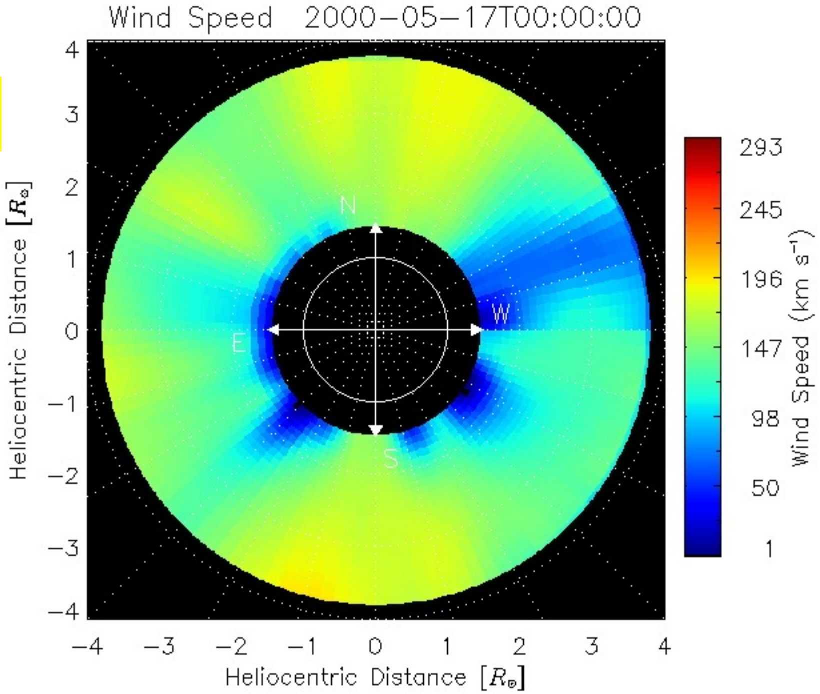
from

UVCS/SoHO

+

LASCO/SoHO/

Giordano+ 2024 in preparation



Doppler Dimming Diagnostic: Parameters

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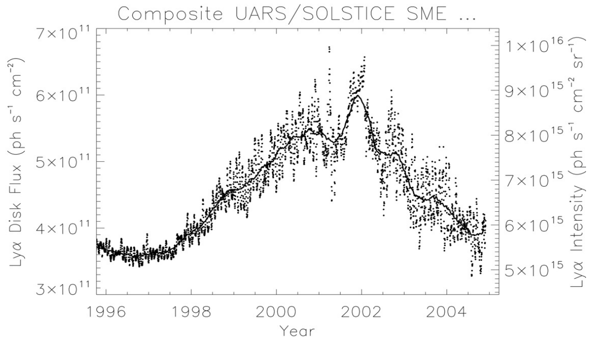
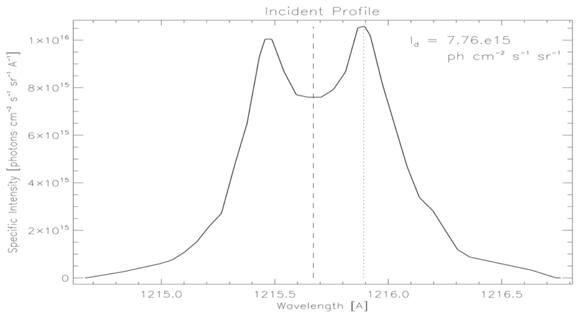
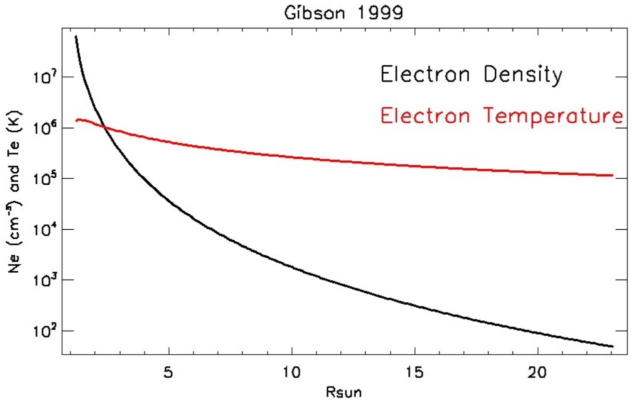






* Dolei+ 2018, ** Dolei+ 2019

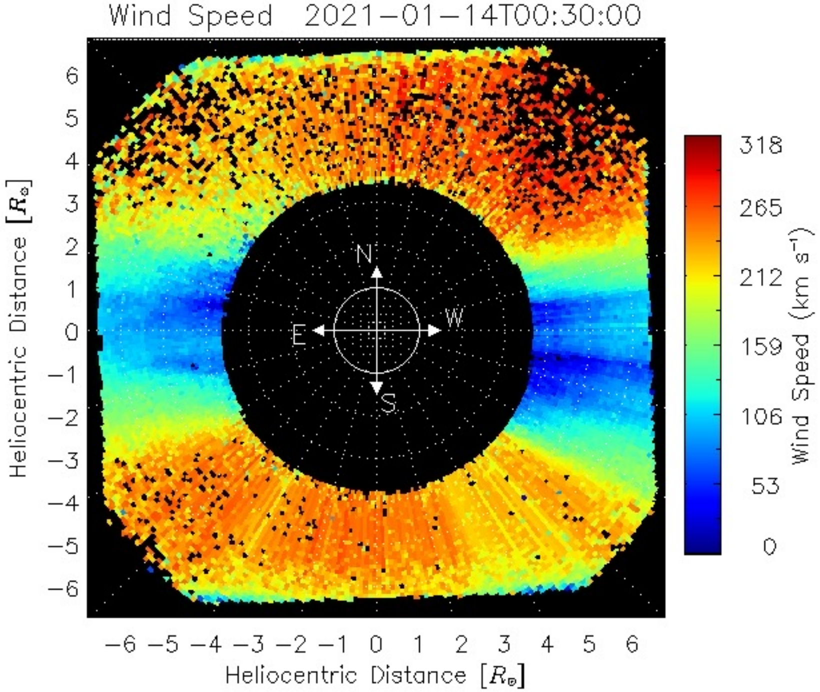
Doppler Dimming Diagnostic: Electron Temperature

T_e Electron Temperature = [0.4, … 1.6]MK

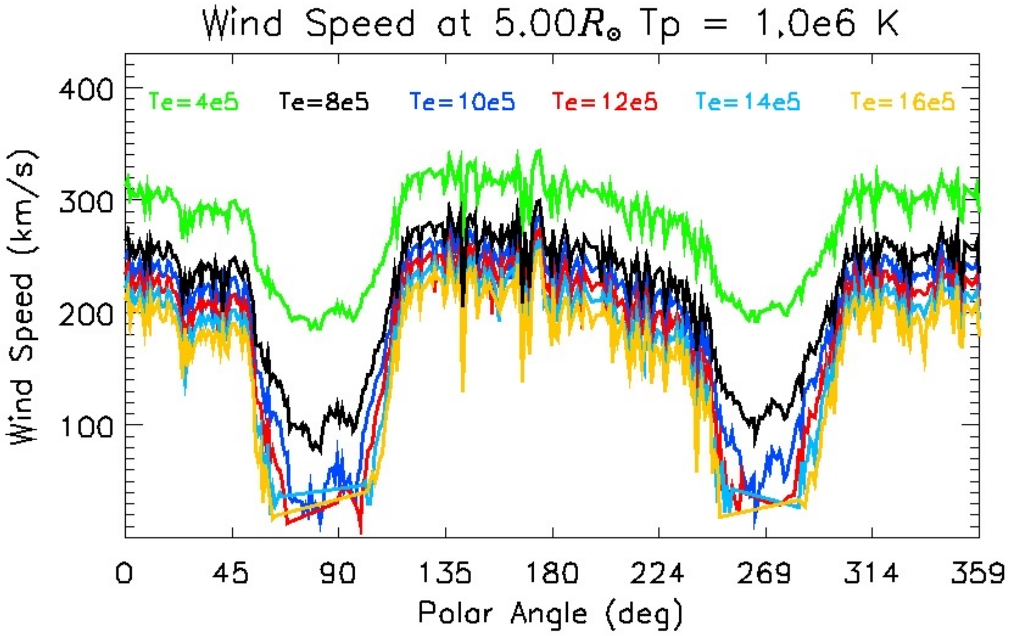
T_p Proton Temperature = [1.0, … 3.0 MK

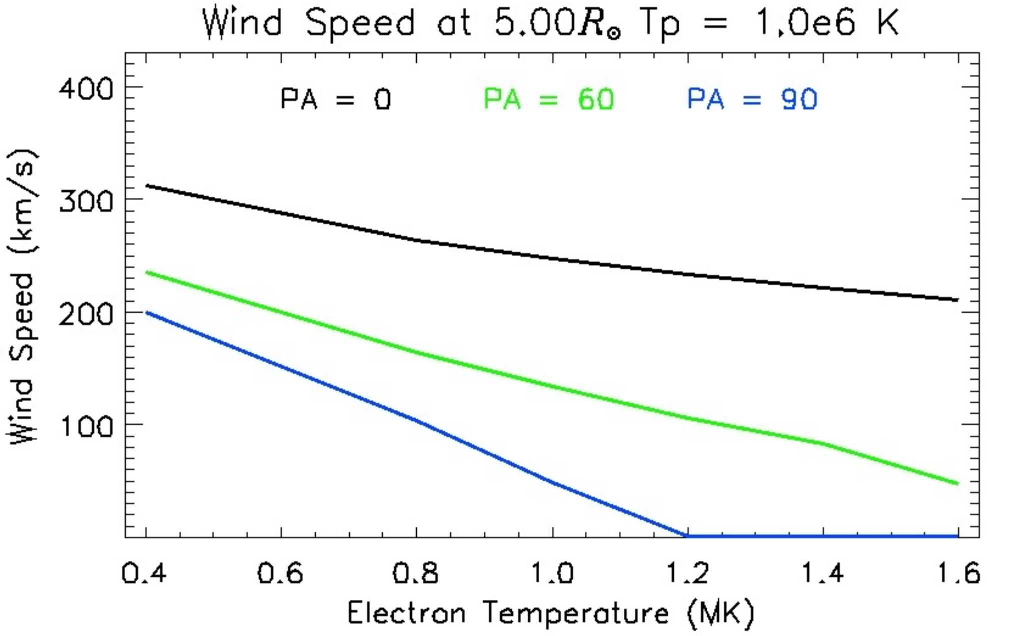
K_i Anisotropy factor = [1, 2]

A_{He} He Abundance = [2.5, 10]%



$T_e = T_p = 1\text{MK}$ $K_i = 1$ $A_{He} = 2.5\%$

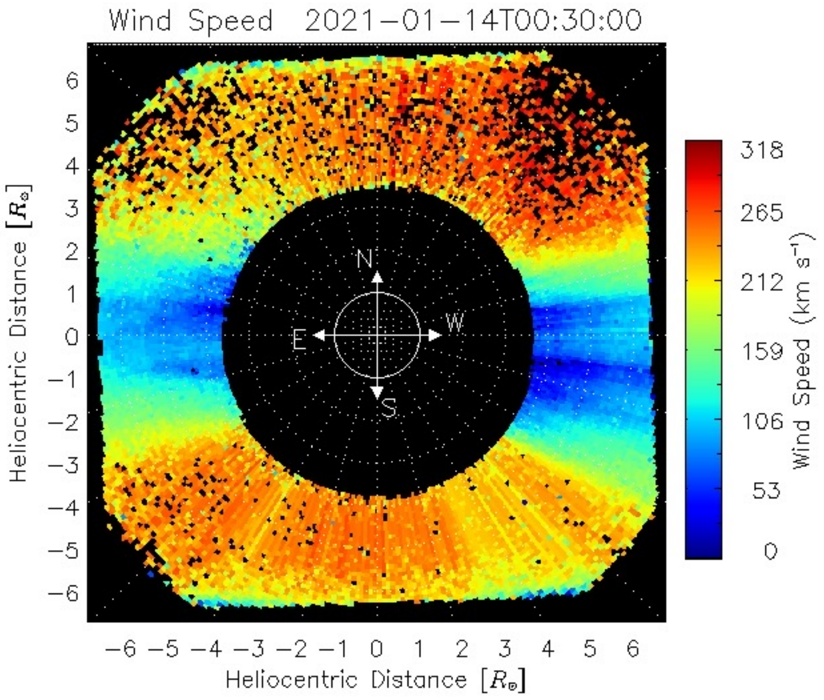


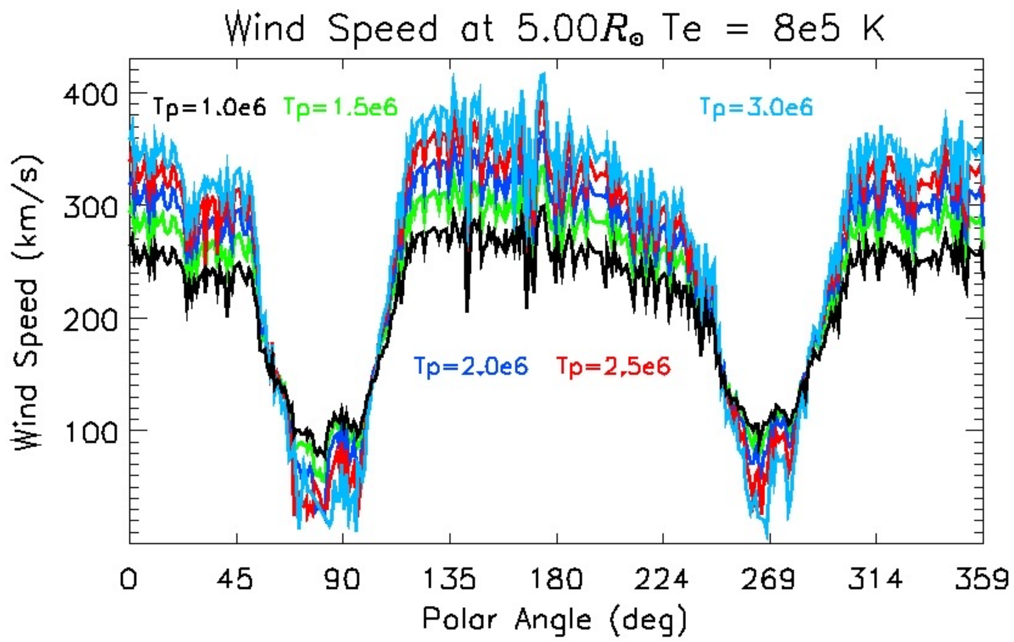


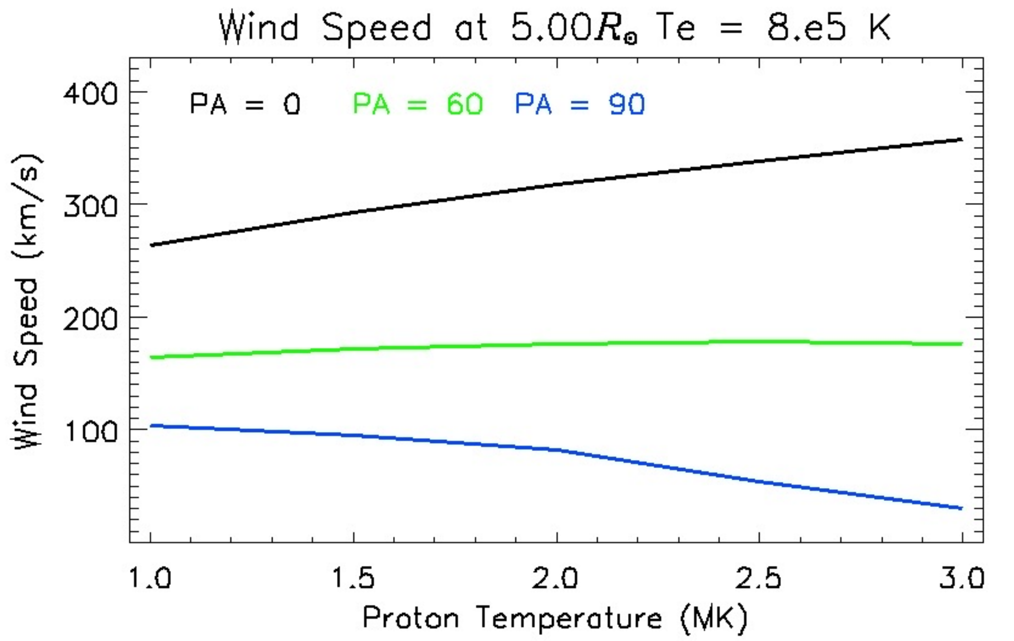
T_e

Doppler Dimming Diagnostic: Proton Temperature

- T_e Electron Temperature = [0.4, … 1.6]MK
- T_p Proton Temperature = [1.0, … 3.0 MK
- K_i Anisotropy factor = [1, 2]
- A_{He} He Abundance = [2.5, 10]%







T_p

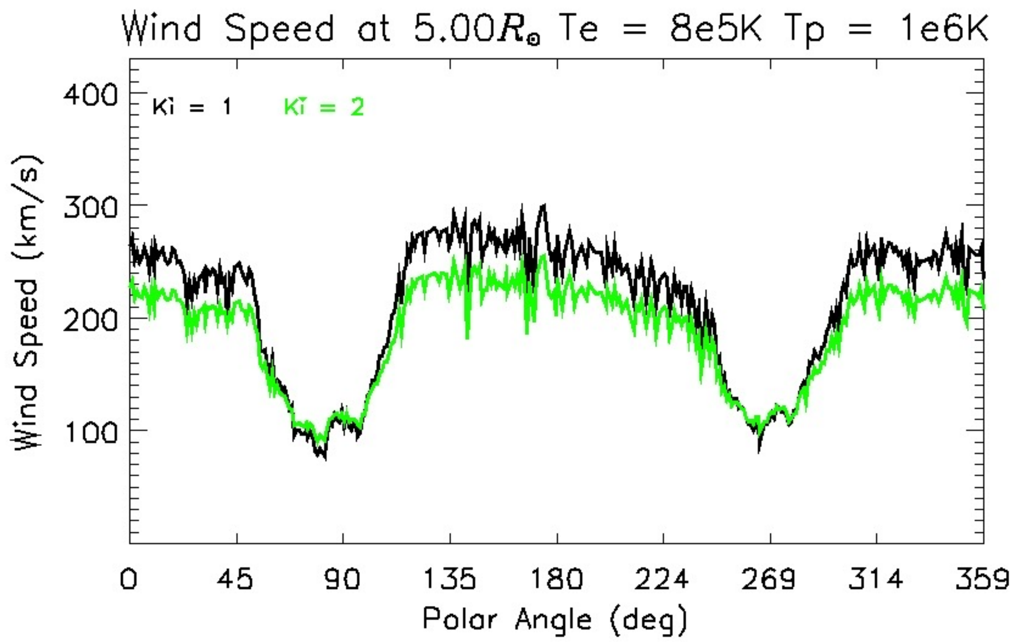
Doppler Dimming Diagnostic: Temperature Anisotropy

T_e Electron Temperature = [0.4, … 1.6]MK

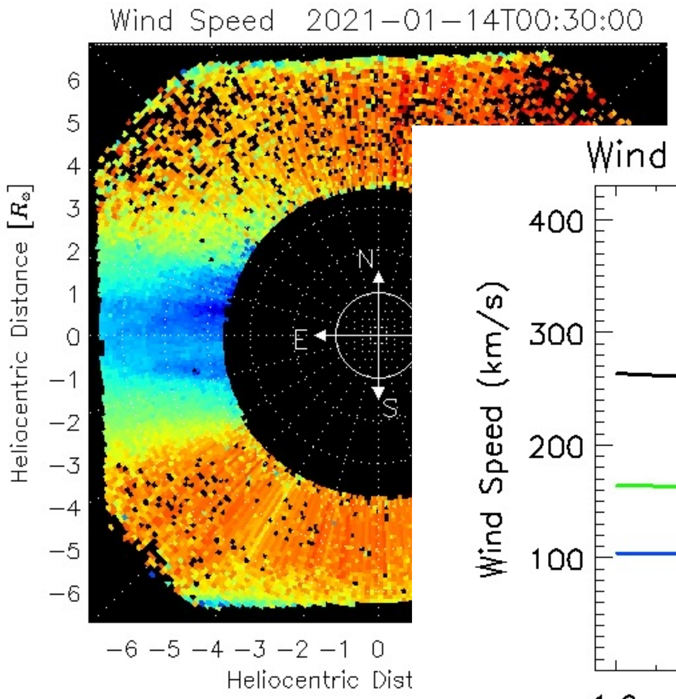
T_p Proton Temperature = [1.0, … 3.0 MK

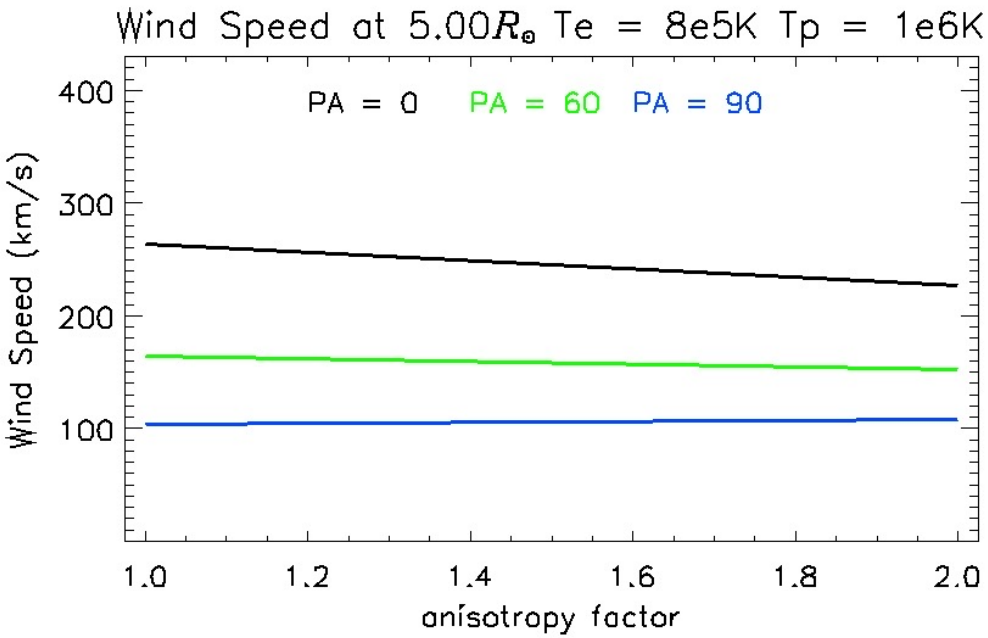
K_i Anisotropy factor = [1, 2]

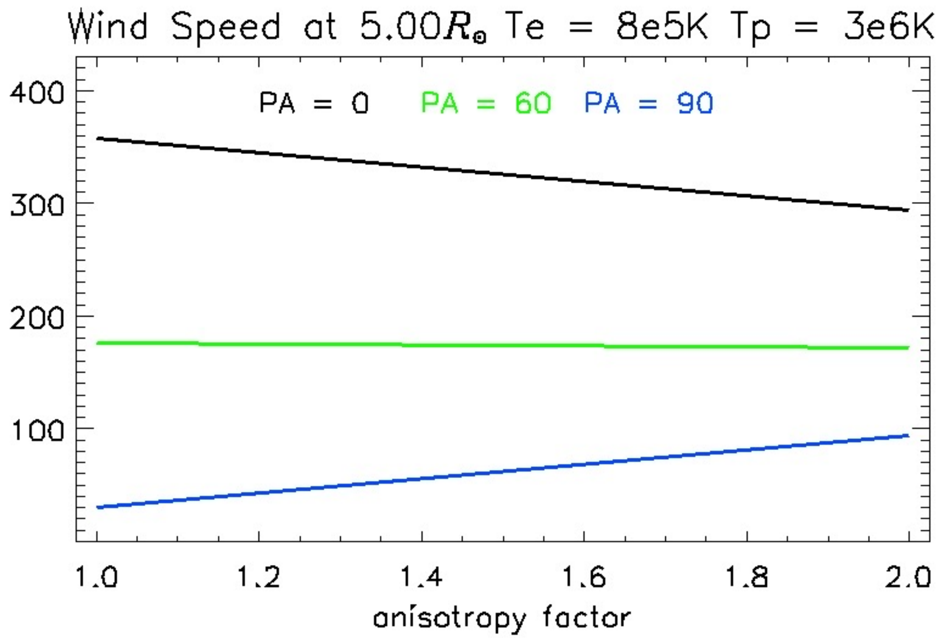
A_{He} He Abundance = [2.5, 10]%



K_i

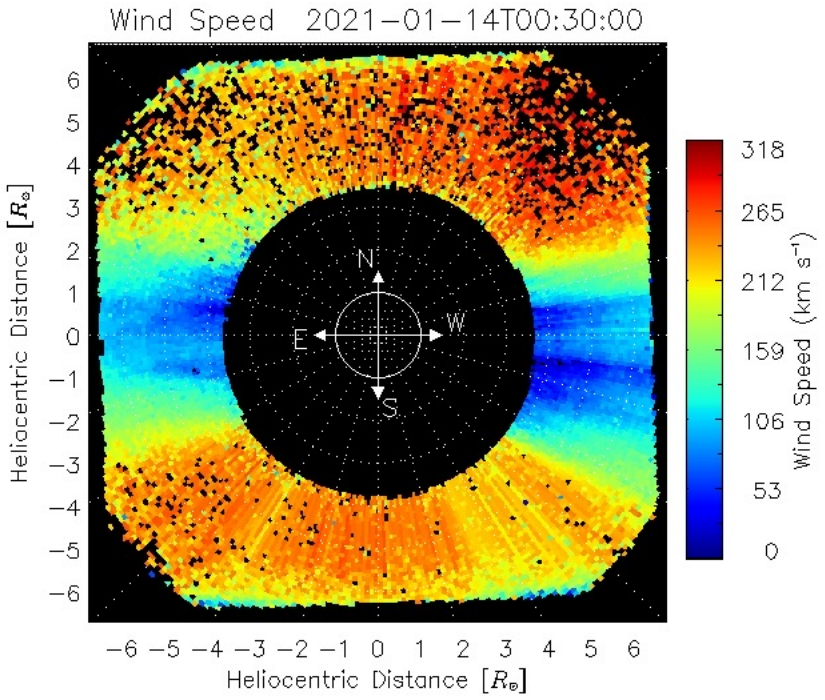


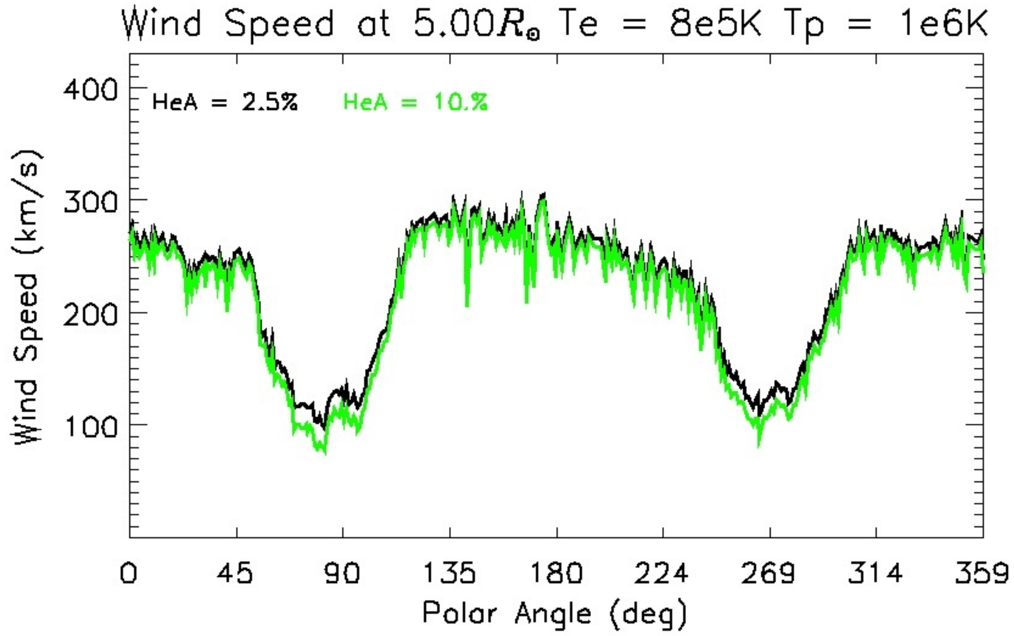




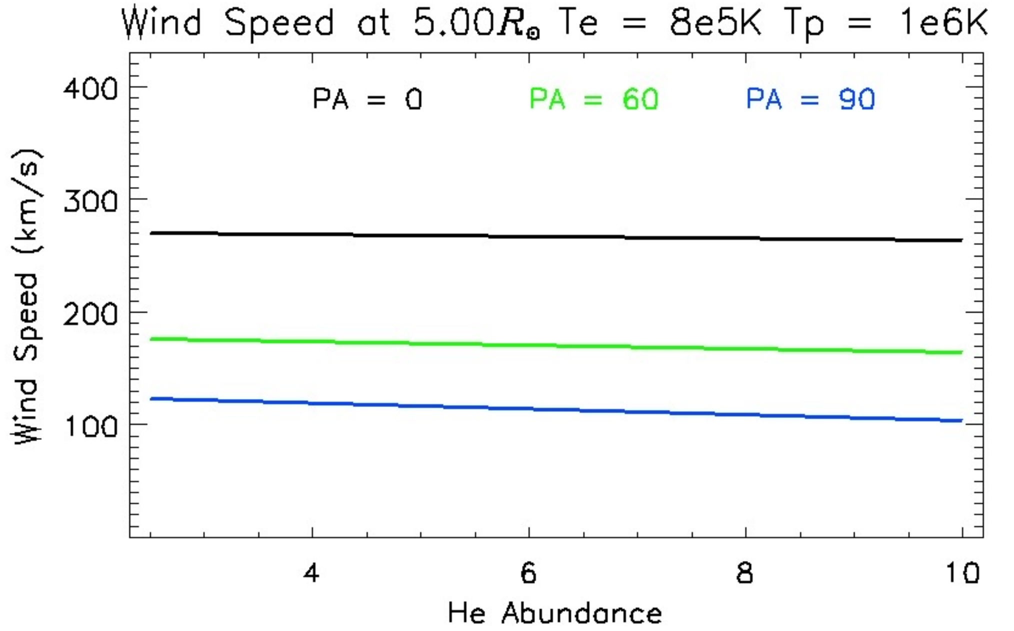
Doppler Dimming Diagnostic: He Abundance

T_e	Electron Temperature	= [0.4, … 1.6]MK
T_p	Proton Temperature	= [1.0, … 3.0 MK
K_i	Anisotropy factor	= [1, 2]
A_{He}	He Abundance	= [2.5, 10]%

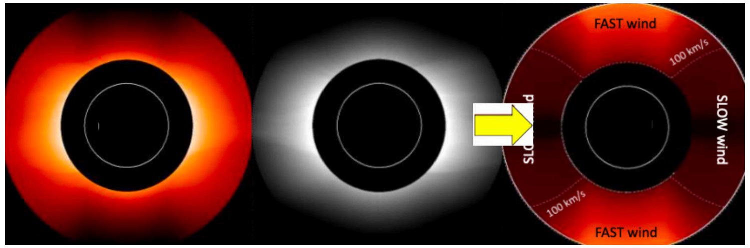




A_{He}



DDT Graphical User Interface



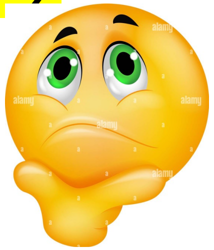
friendly, customizable and documented way
*to make **solar wind speed** maps*
*from a couple of **UV** and **pB** measurements*

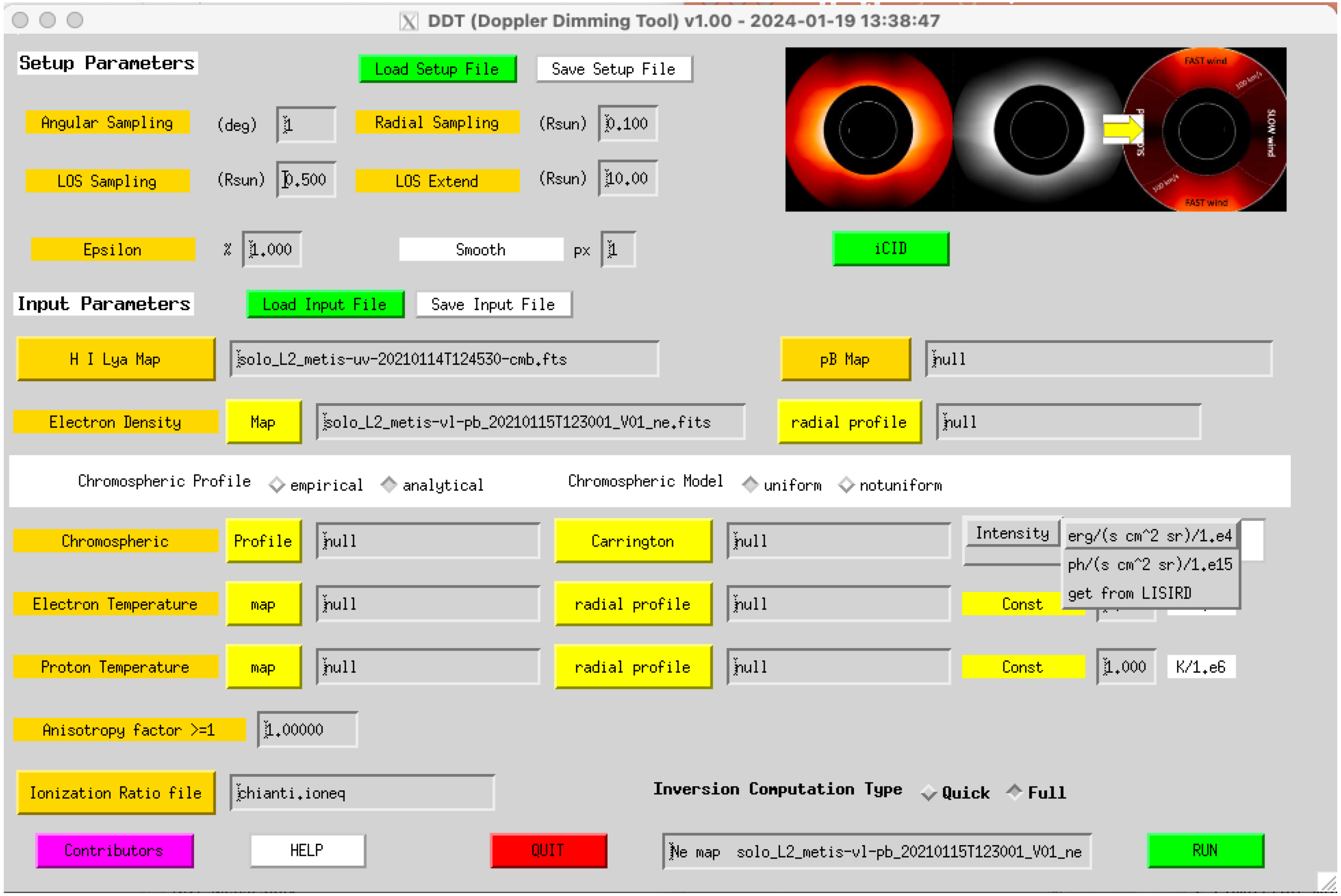
Different assumptions can be adopted (coronal and chromospheric model, geometry and pB inversion)

1. Select different input data (different observations, different instruments, or simulations)
2. Allow setting model/geometry parameters
3. Determine Solar Wind Speed and make maps
4. Save Results and take the record of used parameters → allows parametric studies

DDT Graphical User Interface

- ❑ *customizable*
- ❑ *documented*
- ❑ *friendly*





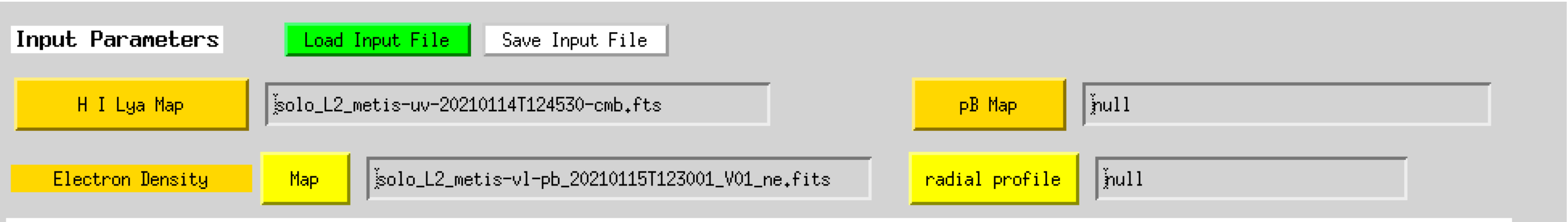
- HowToInstall

```
tar -zxvf ddt_v1.00.tar.gz
```

- HowToRun

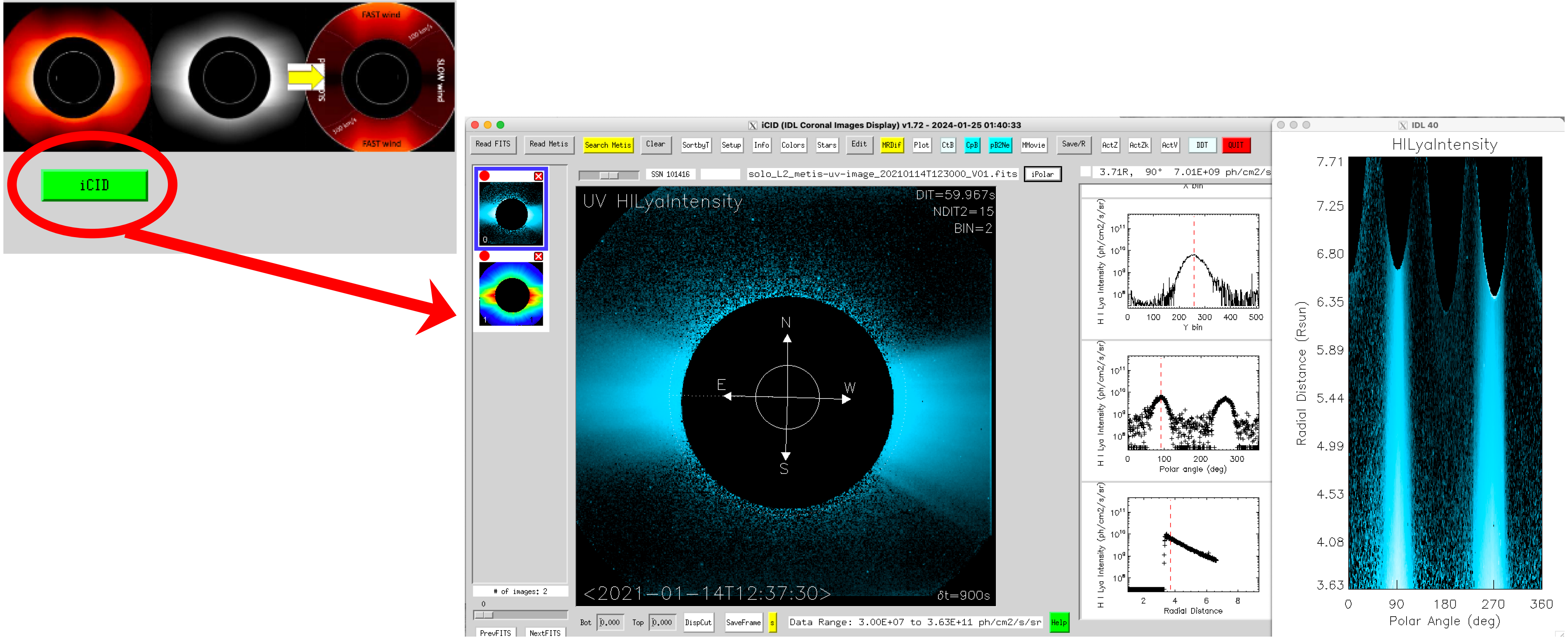
```
cd v1.00/wcode
sswidl
@ddtc
ddt_run,/GUI
```

DDT Graphical User Interface



Set Input from Maps:

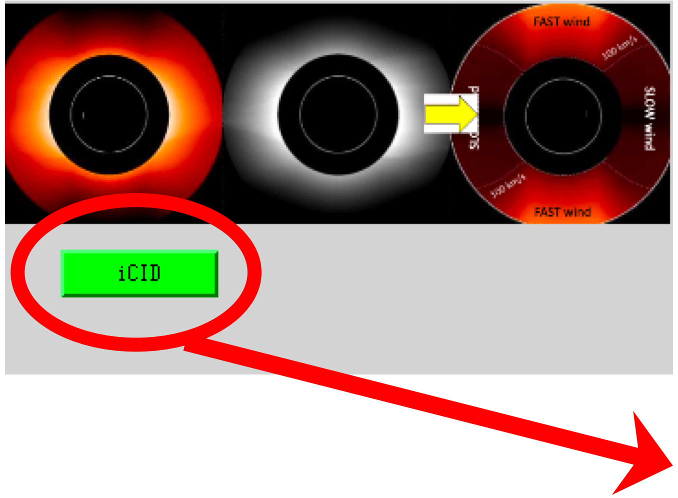
UV and pB (or Electron Density)

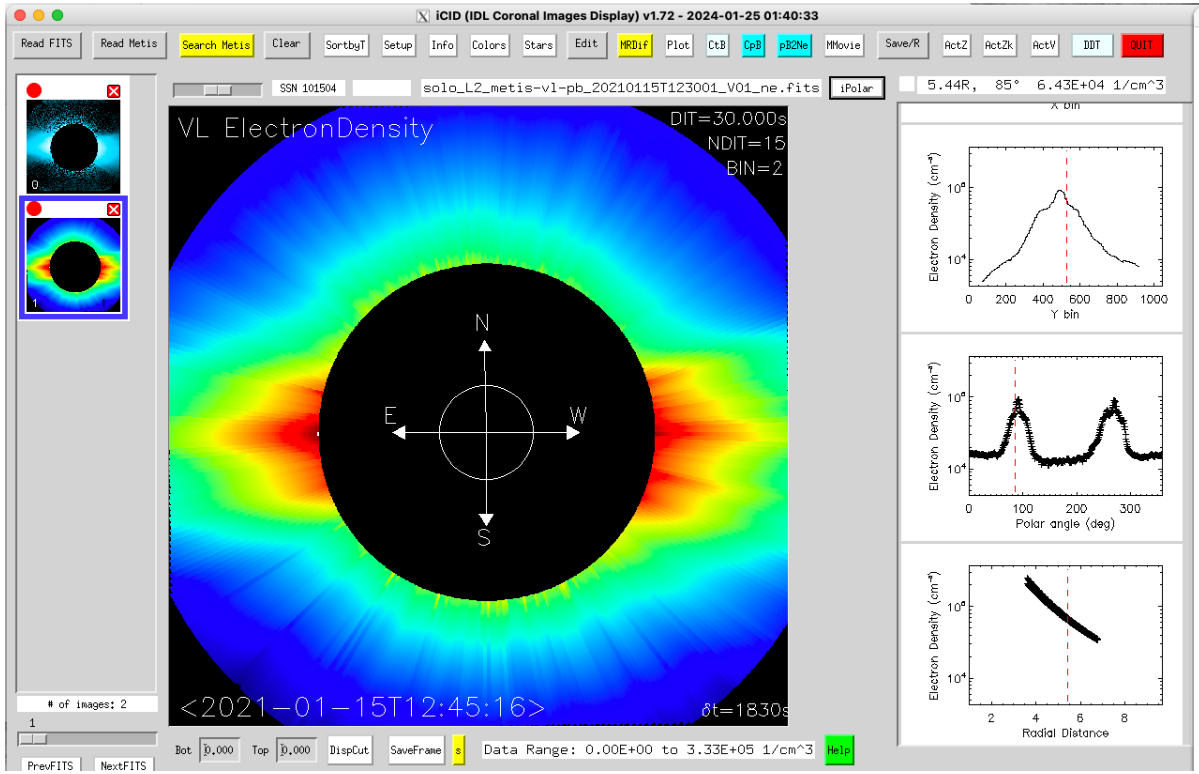


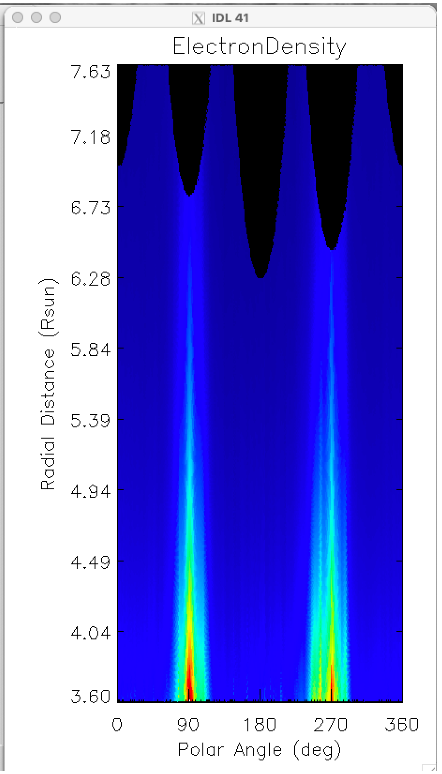
DDT Graphical User Interface

Set Input from Maps:

UV and pB (or Electron Density)

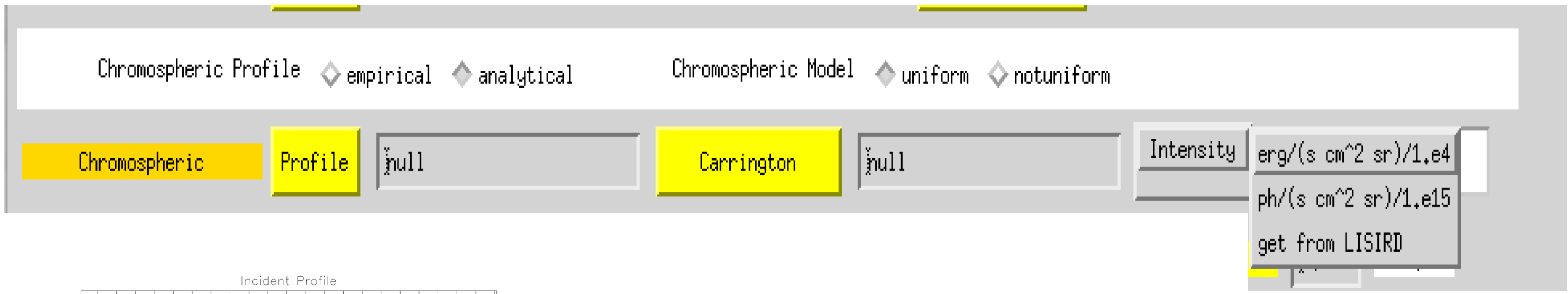


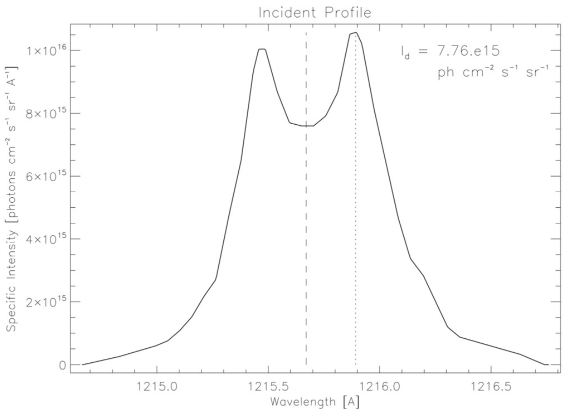




DDT Graphical User Interface

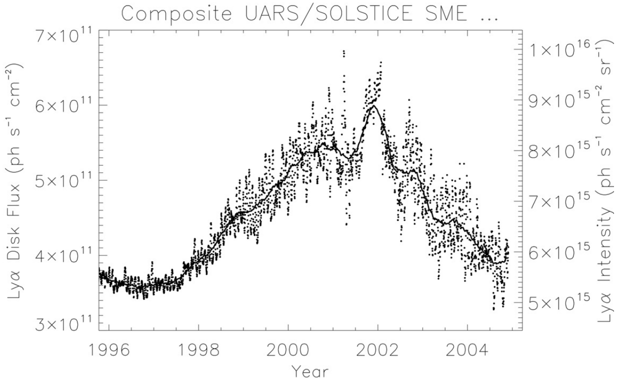
Set Chromospheric Model

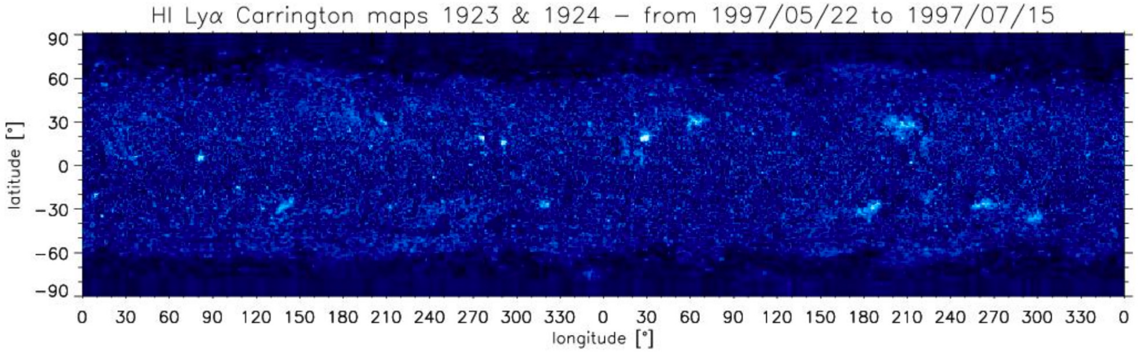




LASP Interactive Solar Irradiance Datacenter

https://lasp.colorado.edu/lisird/





Disk profile:

- Analytical (Auchère 2005)
- Empirical (Lemaire 2000)

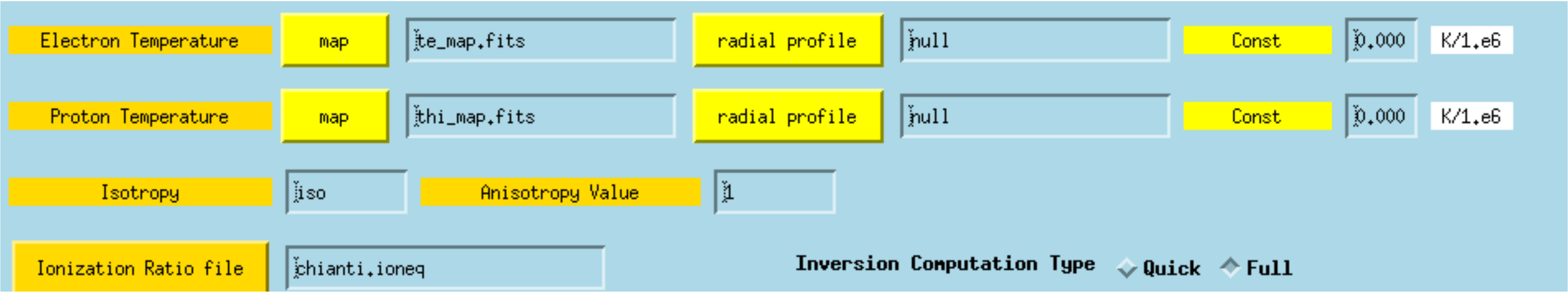
DDT Graphical User Interface

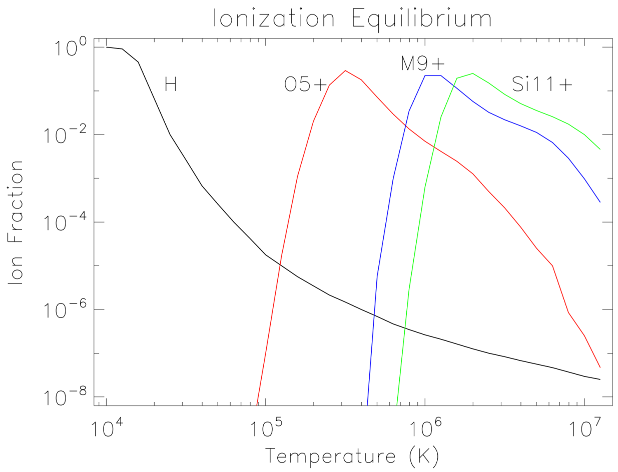
Coronal Model

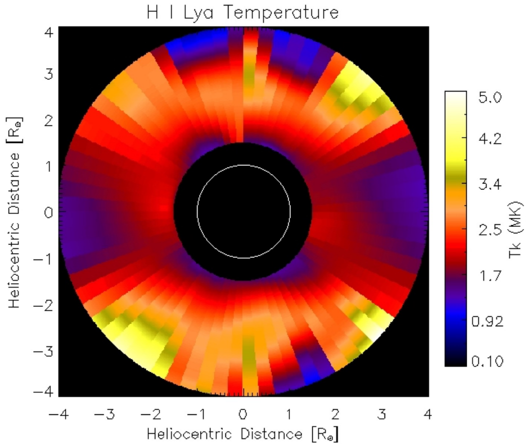
T_e

T_p

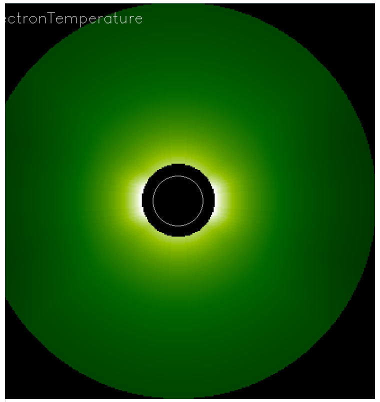
K_i



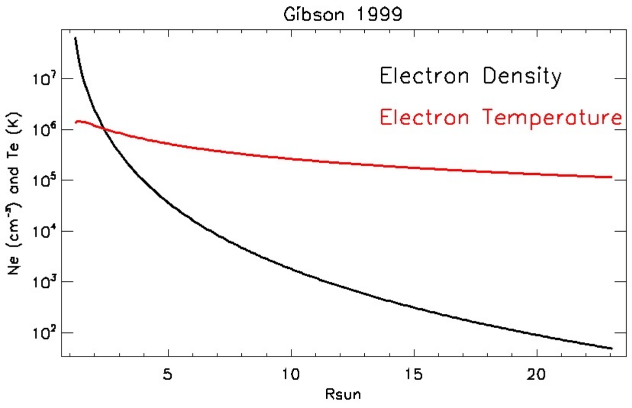




T_{HI}



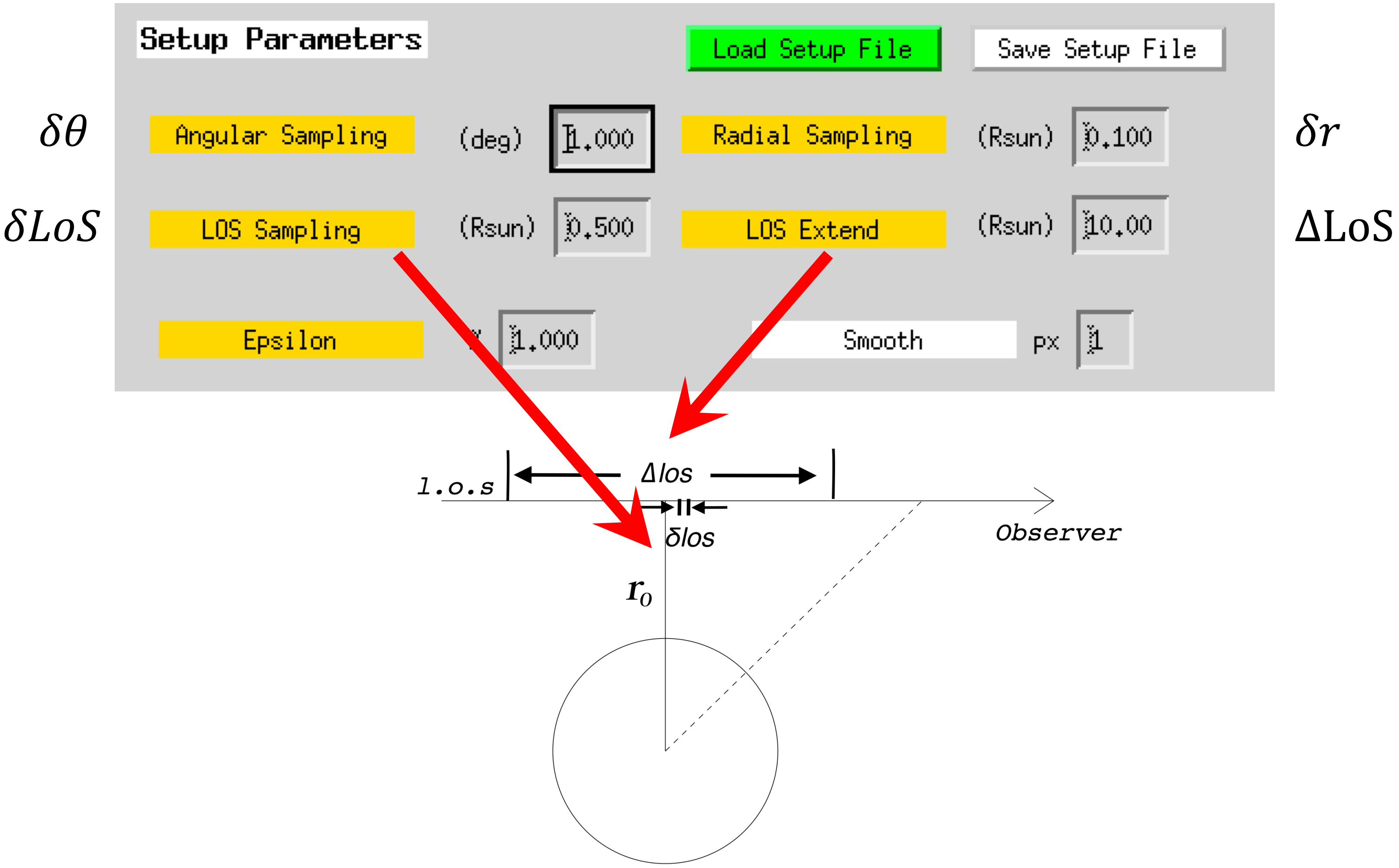
T_e

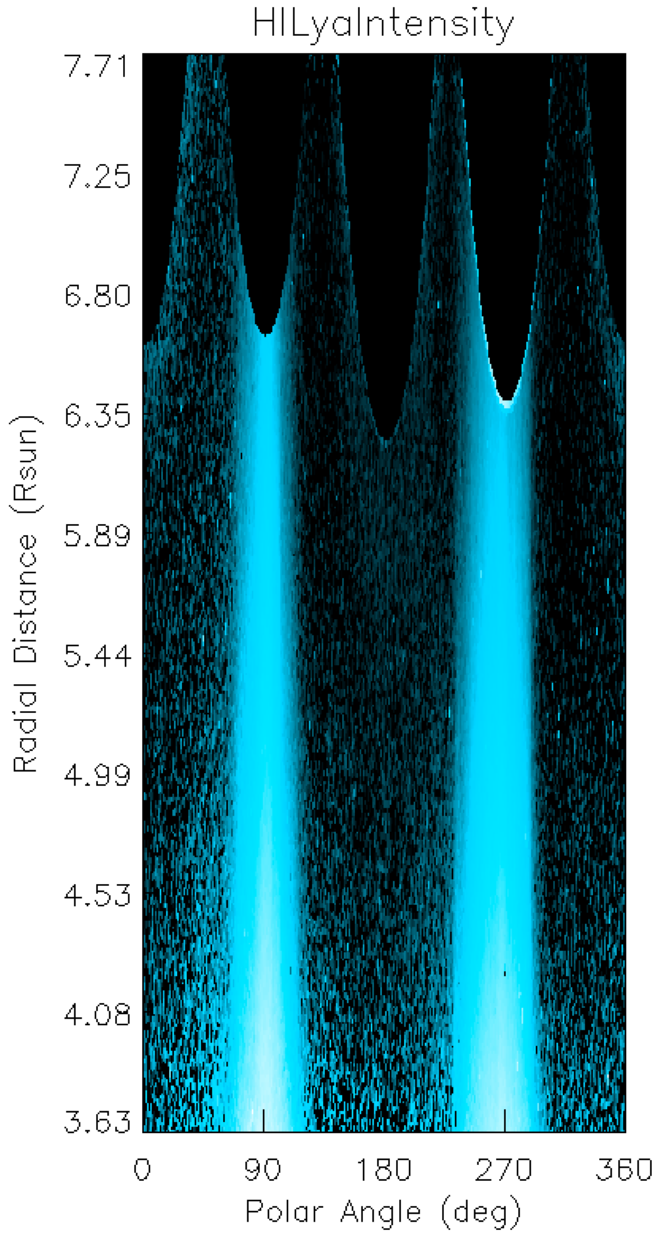


DDT Graphical User Interface

Setup Parameters:

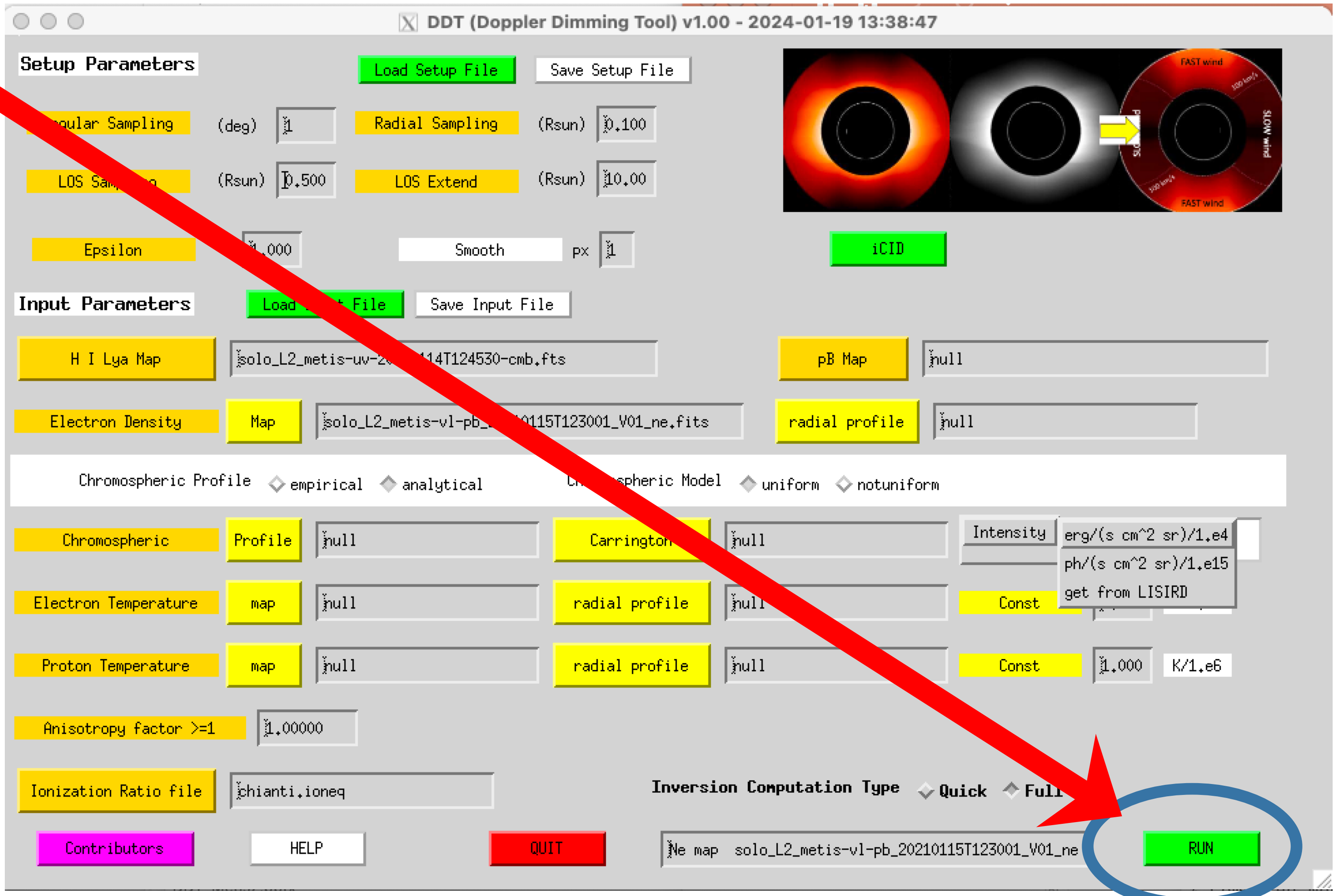
Set Resolutions and Tolerance





DDT Graphical User Interface

Run



The code can be run without the GUI,
by editing the “Setup File” and “Input File”
then executing the command: `ddt_run,/NOGUI`

Setup File

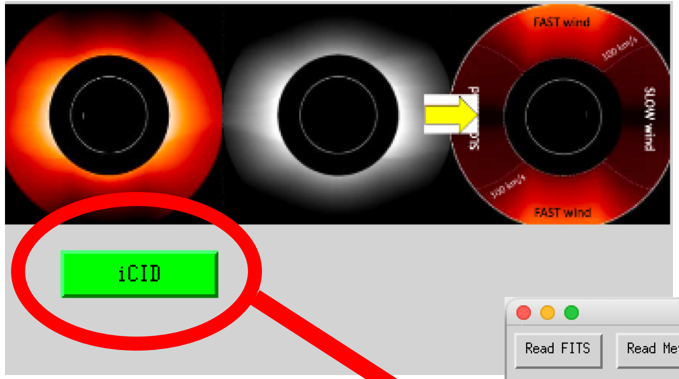
`.. /setup/ddt_setup.txt`

1.00 ; Angular Sampling (Deg)
0.10 ; Radial Sampling (Rsun)
12.00 ; Los Extend (Rsun)
0.50 ; Los Sampling (Rsun)
1.00 ; %Tolerance
../../ddtdata/input/ab/ ; Abundance
../../ddtdata/input/chr/ ; Chromospheric Model
../../docs/ ; Documentation and help
../../ddtdata/input/te/ ; Electron Temperature
../../ddtdata/input/tk/ ; HI Temperature
../../ddtdata/input/uv/ ; HI Ly-Alpha Intensity
../../ddtdata/input/wl/pb/ ; Polarised Brightness
../../ddtdata/input/wl/tb/ ; Total Brightness
../../ddtdata/input/wl/ne/ ; Electron Density
../../ddtdata/wmap/ ; Results

Input File

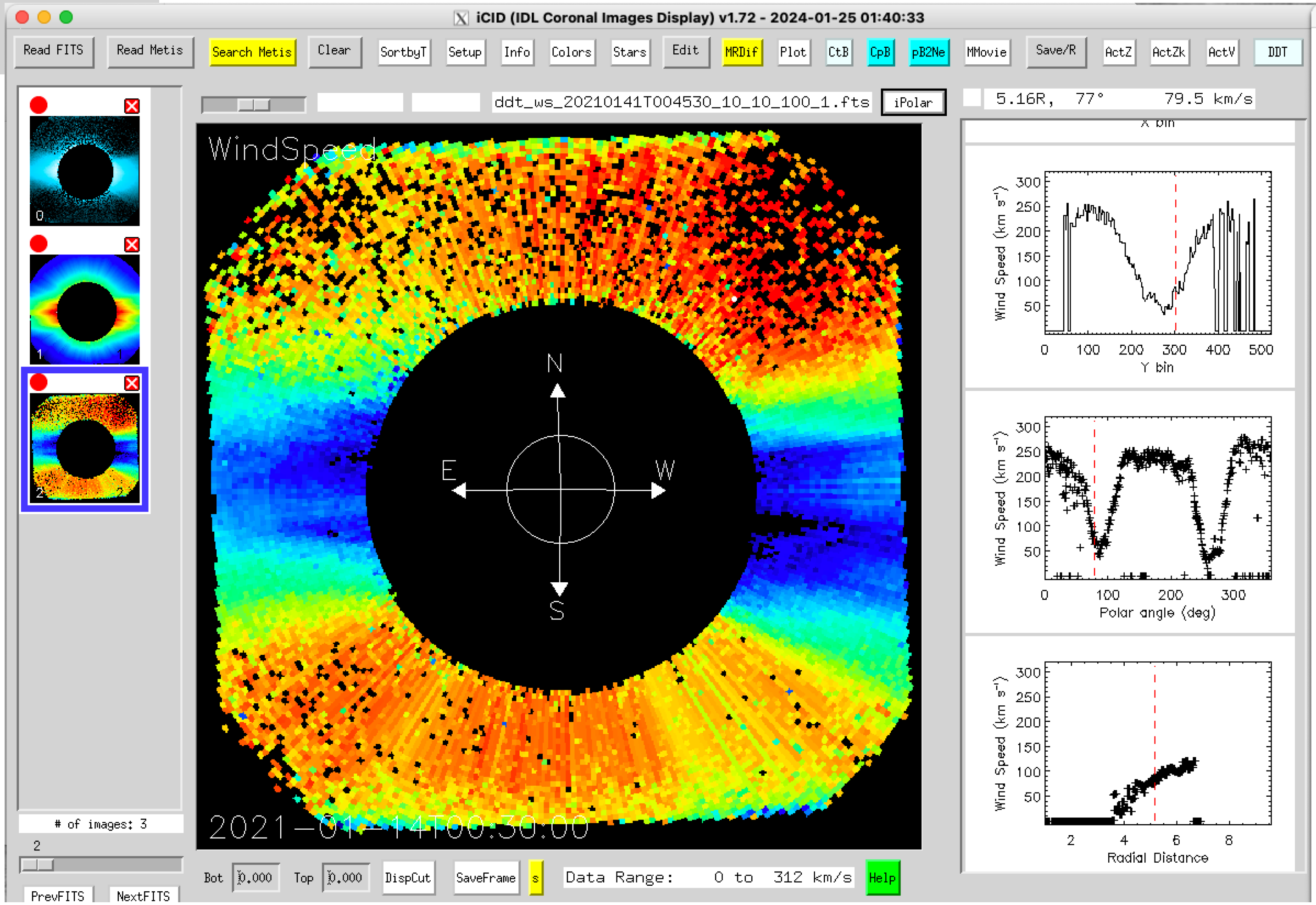
`../ddtdata/input/ddt_input/ddt_input_def.txt`

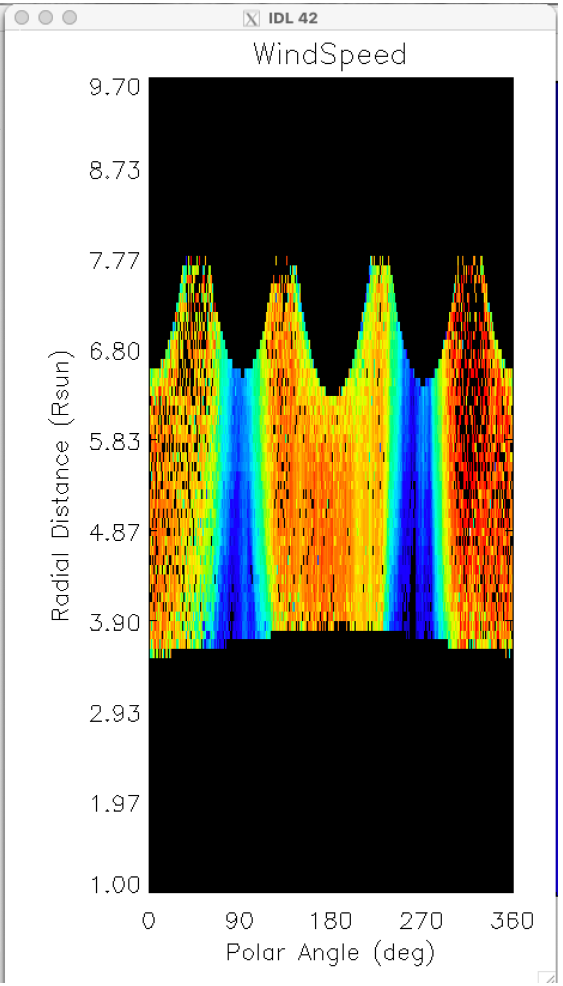
uv_map.fits ; HI Ly-Alpha Intensity Image Fits File
Uniform ; Chromospheric Model 'uniform' 'notuniform'
analytical ; Chromospheric Profile 'empirical, 'analytical'
null ; Empirical Line Profile Data File
null ; Carrington Map Fits File
7.00 ; Constant Chromospheric Intensity
erg/(s cm^2 sr)/1.e4 ; Constant Chromospheric Intensity Unit
pb_map.fits ; Polarised Brightness Fits File (IN MSB)
null ; Electron Density Fits File
null ; Electron Density Data File
null ; Electron Temperature Fits File
null ; Electron Temperature Data File
1.00 ; Constant Electron Temperature (K/1.e6)
1.00 ; Anisotropy Values
thi_map.fits ; HI Temperature Fits File
null ; HI Temperature Data File
0.00 ; Constant Proton Temperature (K/1.e6)
chianti.ioneq ; HI Ionization Fraction Data File
0.10 ; He abundance with respect to H
3.0e7 ; Interplanetary Ly-alpha intensity (phot cm^-2 sr^-1 s^-1)



DDT Graphical User Interface

Display Results : Wind Speed Maps





Maps are saved as

a) FITS files

b) IDL-save files

DDT Documentation

Paper in preparation

Dopper Dimming Tool, DDT, v1.00

Silvio Giordano[1], Luca Zangrilli[1] and Giuseppe Capuano[2]

January 15, 2024

Contents

[1]INAF-Osservatorio Astrofisico di Torino, via Osservatorio 20, 10025 Pino Torinese, Italy

[2]INAF-Osservatorio Astrofisico di Catania, Italy

DDT Documentation

Therefore, the following expressions, relative to the thermal width along $\mathbf{p}$, are obtained:

$$w^2 = w_{x'}^2 \cos^2\theta + w_{y'}^2 \sin^2\theta \cos^2\psi + w_{z'}^2 \sin^2\theta \sin^2\psi$$

$$w = \frac{\lambda_0}{c}\sqrt{\frac{2K}{m}}\sqrt{T_{x'}\cos^2\theta + T_{y'}\sin^2\theta\cos^2\psi + T_{z'}\sin^2\theta\sin^2\psi}$$

The temperature can be decomposed into a component along the line of sight and perpendicular to the coronal magnetic field lines, $T_\perp$, (i.e., along $\mathbf{y}'$ and $\mathbf{z}'$) and a component parallel to the magnetic field assumed as radially, $T_\parallel$ (i.e. along $\mathbf{x}'$).

Defining $T_{x'} = T_\parallel$, $T_{y'} = T_{z'} = T_\perp$, the dependence on ψ vanishes then previous formula becomes:

$$w = \frac{\lambda_0}{c}\sqrt{\frac{2KT_p}{m}} = \frac{\lambda_0}{c}\sqrt{\frac{2K}{m}}\sqrt{T_\parallel\cos^2\theta + T_\perp\sin^2\theta} \quad (36)$$

Introducing an anisotropy factor, $K_i = \frac{T_\perp}{T_\parallel}$ we write equation 36 as:

$$w = \frac{\lambda_0}{c}\sqrt{\frac{2KT}{m}}\sqrt{\frac{\cos^2\theta}{K_i} + \sin^2\theta}$$

13.3.2. Isotropic H I temperature

In case of isotropic H I temperature distribution, ($T_p = T_{x'} = T_{y'} = T_{z'} = T$, i.e. $T_\parallel = T_\perp$) Eq. 36 is equal to Eq. 28, thus the width of the absorption profile, w, does not depend on θ and ψ.

Both in the isotropic and anisotropic cases, if the chromospheric intensity $I_t(\mathbf{n}')$ is assumed to be uniform over the solar disk ($I_t(\mathbf{n}')$=I_t), the integral over ψ in Eq. 33 can be solved analytically.

Taking into account the first expression in Eq. 42, the integral over the angle ψ in Eq. 33 is similar to

$$\int_0^{2\pi}[a + b(\mathbf{n}\cdot\mathbf{n}')^2]d\psi = 2\pi a + b\int_0^{2\pi}(n'_{x_e})^2 d\psi \quad (37)$$

where

$$(n'_{x_e})^2 = (\cos\phi_c\cos\theta - \sin\phi_c\cos\psi\sin\theta)^2 =$$
$$= \cos^2\phi_c\cos^2\theta - 2\cos\phi_c\cos\theta\sin\phi_c\cos\psi\sin\theta + \sin^2\phi_c\cos^2\psi\sin^2\theta$$

and a and b are, respectively, 11/12 and 3/12.

Then, the second term of Eq. 37 is

$$b\int_0^{2\pi}(n'_{x_e})^2\, d\psi =$$
$$= b\int_0^{2\pi}(\cos^2\phi_c\cos^2\theta - 2\cos\phi_c\cos\theta\sin\phi_c\cos\psi\sin\theta + \sin^2\phi_c\cos^2\psi\sin^2\theta)\, d\psi =$$
$$= b\int_0^{2\pi}\cos^2\phi_c\cos^2\theta\, d\psi - b\int_0^{2\pi}2\cos\phi_c\cos\theta\sin\phi_c\cos\psi\sin\theta\, d\psi + b\int_0^{2\pi}\sin^2\phi_c\cos^2\psi\sin^2\theta\, d\psi =$$
$$= 2\pi b\cos^2\phi_c\cos^2\theta - 2b\cos\phi_c\cos\theta\sin\phi_c\sin\theta\int_0^{2\pi}\cos\psi\, d\psi + b\sin^2\phi_c\sin^2\theta\int_0^{2\pi}\cos^2\psi\, d\psi$$

In the last equation, the middle term is equal to zero, from which

$$b\int_0^{2\pi}(n'_{x_e})^2 d\psi = 2\pi b\cos^2\phi_c\cos^2\theta + b\sin^2\phi_c\sin^2\theta\int_0^{2\pi}\cos^2\psi\, d\psi$$

where the last integral can be written as

$$\int_0^{2\pi}\cos^2\psi\, d\psi = \int_0^{2\pi}\frac{1+\cos 2\psi}{2}\, d\psi = \frac{1}{2}\Big[\phi + \sin\psi\cos\psi\Big]_0^{2\pi} = \pi \quad (38)$$

Therefore, Eq. 37 can be rewritten:

$$\int_0^{2\pi}[a + b(\mathbf{n}\cdot\mathbf{n}')]d\psi = 2\pi a + 2\pi b\cos^2\phi_c\cos^2\theta + \pi b\sin^2\phi_c\sin^2\theta =$$
$$= 2\pi\left(a + b\cos^2\phi_c\cos^2\theta + \frac{b}{2}\sin^2\phi_c\sin^2\theta\right)$$

In conclusion, the expression of the synthetic coronal intensity, in the case of isotropic H I temperature ($T_\perp$=$T_\parallel$), becomes (see Eq. A.4 in Dolei et al. 2019)

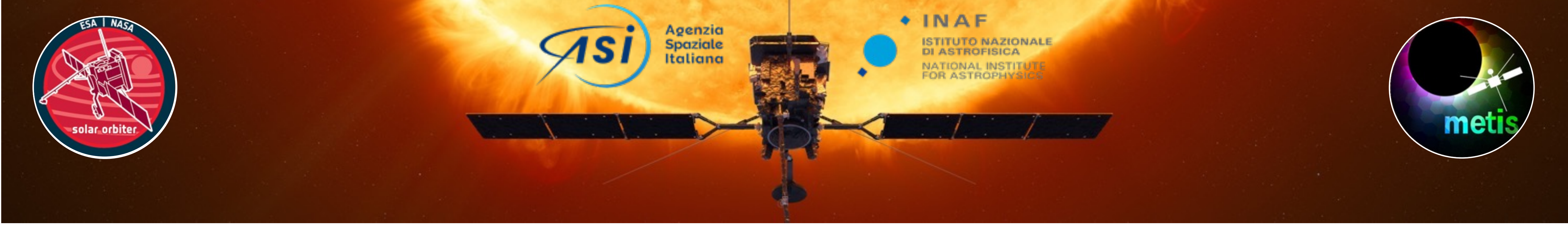
$$I_r(\mathbf{n}) = \frac{1}{\sum_{i=1}^n a_i}\frac{n_{pe}\, hB_{12}}{2\sqrt{\pi}\lambda_0}I_t\int_{-\infty}^{+\infty}n_e\, R_H dx\int_0^{\alpha_2}\left[\frac{11}{12} + \frac{3}{12}\cos^2\phi_c\cos^2\theta + \frac{1}{2}\frac{3}{12}\sin^2\phi_c\sin^2\theta\right]$$
$$\times\sum_{i=1}^n\frac{a_i}{\sqrt{w^2+\sigma_i^2}}\exp\left[-\frac{(\delta\lambda_i - \frac{\lambda_0}{c}v_w\cos\theta)^2}{w^2+\sigma_i^2}\right]\sin\theta\, d\theta \quad (39)$$

In Table 3 a summary of the expressions concerning the described cases is reported:

Table 3: Summary of the resonant coronal intensity expressions linked to the described coronal conditions. The chromospheric intensity is supposed constant.

Chromospheric profile: empirical
$I_r(\mathbf{n}) = \frac{n_{pe}\, hB_{12}}{2\lambda_0}\int_{-\infty}^{+\infty}n_e\, R_H dx$ $\times\int_\theta\left[\frac{11}{12} + \frac{3}{12}\cos^2\phi_c\cos^2\theta + \frac{1}{2}\frac{3}{12}\sin^2\phi_c\sin^2\theta\right]F(\mathbf{n}', v_w, \theta)\sin\theta\, d\theta$
Chromospheric profile: analytical
$I_r(\mathbf{n}) = \frac{1}{\sum_{i=1}^n a_i}\frac{n_{pe}\, hB_{12}}{2\sqrt{\pi}\lambda_0}I_t\int_{-\infty}^{+\infty}n_e\, R_H dx$ $\times\int_\theta\left[\frac{11}{12} + \frac{3}{12}\cos^2\phi_c\cos^2\theta + \frac{1}{2}\frac{3}{12}\sin^2\phi_c\sin^2\theta\right]\sum_{i=1}^n\frac{a_i}{\sqrt{w^2+\sigma_i^2}}\exp\left[-\frac{(\delta\lambda_i - \frac{\lambda_0}{c}v_w\cos\theta)^2}{w^2+\sigma_i^2}\right]\sin\theta\, d\theta$

Thanks to G. Capuano



Conclusions "A software tool for computing Solar Wind Speed through Doppler dimming diagnostics"

Doppler Dimming Tool (DDT)

- ✓ Beta version released to Metis team
- ✓ Documentation ready … paper in progress
- ✓ Plan for public release
  - ➡️ IDL (v1.0 ready) ……
  - ➡️ Python (in progress)

Solar Wind Speed Maps

- ✓ Metis: plan to release as L3 data (with a standard set of model parameters)
- ✓ UVCS: variation of wind speed through solar cycle 23 … in progress

Incoming Work

- ✓ Go beyond the cylindrical geometry
- ✓ Include Diagnostics from other spectral lines, e.g. O vi 1032A 1037A, He ii 304A